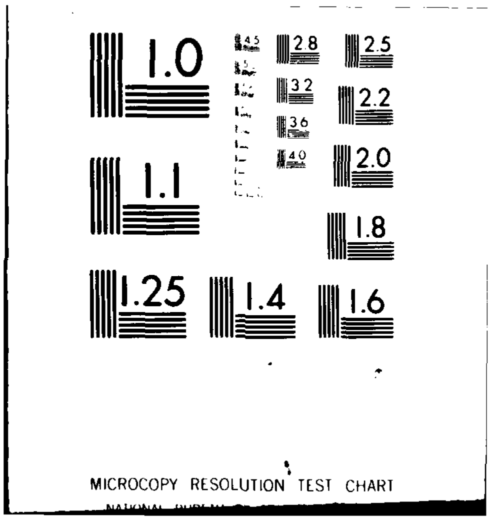
AD-A098 581 VIRGINIA UNIV CHARLOTTESVILLE DEPT OF ENVIRONMENTAL --ETC F/G 4/2
SPATIAL AND TEMPORAL VARIATIONS IN CYCLONE FREQUENCY PATTERNS.(U)
APR 81 B P HAYDEN, R DOLAN, W SMITH N00014-81-K-0033
UNCLASSIFIED TR-21 NL

1 OF 2
AD A
098581


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART

TR-2

12

CLASSIFICATION OF COASTAL ENVIRONMENTS

TECHNICAL REPORTS 21-24

SPATIAL AND TEMPORAL VARIATIONS IN CYCLONE FREQUENCY PATTERNS

10

Bruce P. Hayden
Robert Dolan
William Smith

14 TR-21, TR

Department of Environmental Sciences
University of Virginia

11

APRIL 1981

OFFICE OF NAVAL RESEARCH GEOGRAPHY PROGRAMS

15 N00014-81-K-0033 — TASK #NR389 170

APPROVED FOR PUBLIC RELEASE

DISTRIBUTION UNLIMITED

CONTENTS:

Technical Report No. 21

ATLANTIC COAST EXTRATROPICAL CYCLONES: CHARACTERISTIC FREQUENCY PATTERNS AND THEIR SECULAR VARIATION

Bruce Hayden

Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

January 1980

Geography Programs
Office of Naval Research
Contract No. N00014-81-K-0033

Reprint from Preprint Volume,
Second Conference on Coastal Meteorology
January 30-February 1, 1980

Reprinted from Preprint Volume: Second Conference on Coastal Meteorology. January 30,- February 1, 1980, Los Angeles, Calif. Published by the American Meteorological Society, Boston, Mass.

ATLANTIC COAST EXTRATROPICAL CYCLONES: CHARACTERISTIC FREQUENCY PATTERNS AND THEIR SECULAR VARIATION

Bruce P. Hayden

University of Virginia
Charlottesville, Virginia

1. INTRODUCTION

Damaging waves and storm surges along the U.S. Atlantic Coast are largely due to extratropical cyclones. Along most of this coast, shorelines are receding (U.S. Army Corps of Engineers, 1971; Dolan et al., 1979). The erosion trend is attributed to the current rise in sea level (Bruun, 1962), lower average cyclone central pressure (Mather, Adams, and Yoshioka, 1964), reduced coastal sand supply (Hoyt, 1967), human activities (Dolan, Godfrey, and Odum, 1973), and to secular variation in cyclone frequency, magnitude and duration (Hayden, 1975). More recently, changes in the tracks of cyclones along the Atlantic coast have been reported (Resio and Hayden, 1975; Dickson and Namias, 1976). Changes in the track of cyclones relative to the coast give rise to variations in breaker heights and storm surge heights at the coast (Resio and Hayden, 1975).

The Resio and Hayden study is limited by the small reach of coast studied and the Dickson and Namias study by the short time span analyzed (1948-1975). In this report, spatial and temporal variations in cyclone frequencies are examined for the 94 years between 1885 and 1978. The study area is Eastern North America and the Western North Atlantic east of the 100th meridian and south of the 50th parallel (Fig. 1).

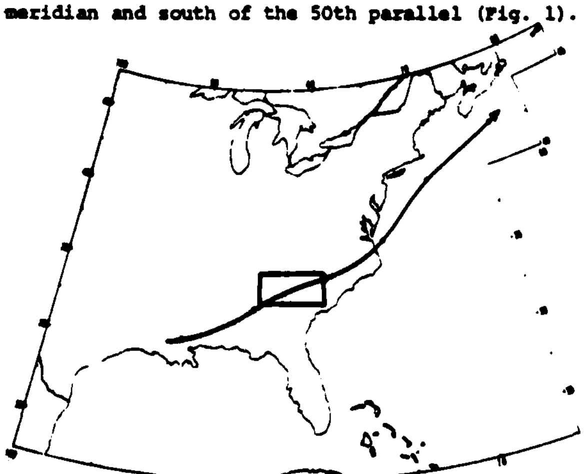


Figure 1. Chart of the study area. The rectangular inset is 2.5° latitude by 5.0° longitude. There are 74 such rectangular grid cells in the study area. The arrow represents a storm track passing through the grid cell shown.

2. EARLIER WORK ON CYCLONE FREQUENCIES

Petterssen (1950) mapped the geographical frequencies of cyclones in the Northern Hemisphere using daily sea-level Historical Weather Maps for the period 1899-1939. Petterssen's map shows a frequency maximum along the east coast of the U.S. as far south as Florida. Klein (1957) attributes the east coast cyclone frequency maximum to an "Atlantic seaboard" cyclone track. Cyclogenesis associated with this track occurs along the tier of Gulf Coast states or along the Virginia Capes. Reed (1960) indicates in his maps of percentage frequency of fronts that the front frequency maximum also parallels the east coast margin but at some distance offshore during the years 1952-1956. Miller (1946) analyzed cyclogenesis for the mid-Atlantic coastal region and found two distinct types. His Type A form largely to the north of Cape Hatteras, North Carolina, and Type B to the south of the Cape. While seasonal variations in cyclone frequency, front frequency and track locations are discussed in some detail, temporal variations were not studied.

More recent studies of cyclones along the Atlantic coast have focused on the generation of potentially damaging waves and surges. Bosserman and Dolan (1968) show an increase in the frequency of storms that generate deep-water waves of 1.3 m or greater from 1942 to 1967. The Bosserman and Dolan study was updated by Hayden (1975). Hayden concluded that the number, severity and duration of Atlantic coast storms had increased between 1942 and 1974. Increases in cyclone severity are also reported by Mather et al., (1964) and they attribute the changes to decreased central pressures between the 1920's and 1960's. Resio and Hayden (1975) found that cyclones tracking along the U.S. Gulf Coast and the genesis of new cyclones along the mid-Atlantic coast had increased from the 1920's to the 1960's. The pre-1920's period more closely resembled the 1960's than the years following the 1920's. Resio and Hayden also showed that the increased severity of Atlantic coastal storms resulted from a seaward displacement of mean storm tracks. They attributed this change to increased blocking in the high latitudes. Dickson and Namias (1976) identified blocking in the Greenland area and cooler than normal temperatures in the U.S. Southeast as the cause of increased frequencies of cyclones off the Atlantic coast between the 1940's, and the 1950's and 1960's.

3. THE DATA

Cyclone frequencies for each year (1885-1978) were tabulated for the 74, 2.5°-latitude by 5.0°-longitude grid cells comprising the study area shown in Figure 1. From monthly charts of the "Tracks of the Centers of Cyclones at Sea Level" published by the Monthly Weather Review and in recent years by the Mariners Weather Log, annual totals of cyclones passing through each grid cell were recorded. Multiple entries of a given storm in a grid cell were ignored. The resulting data matrix has the dimensions of 74 grid-cell-variables and 94 annual cases.

4. LONG-TERM MEANS AND VARIANCES

Figure 2 shows the mean annual frequency of cyclones for the period 1885-1978. In general the frequency of cyclones increases with latitude and with proximity to the U.S. east coast. The axis of the east coast frequency maximum is centered over the coast from Nova Scotia to Georgia. The location of this frequency maximum coincides with the baroclinic zone separating the cold mainland from the warmer ocean waters.

The standard deviation of annual cyclone frequencies is presented in Figure 3. The dominant feature shown by the chart is the pronounced frequency maximum offshore. The axis of this maximum is seaward of the maximum in the mean field (Fig. 2) and apparently rotated clockwise several degrees. The location of the standard deviation maximum more closely approximates the locus of the Gulf Stream than the continental margin. The standard deviations landward of the margin of the east coast are rather modest suggesting that the axis of yearly storm occurrences may expand eastward but in general not over the mainland.

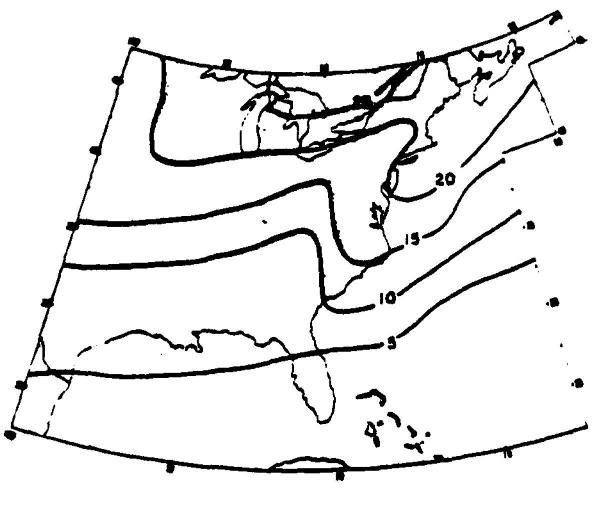


Figure 2. Mean annual cyclone frequency for the years 1885-1978.

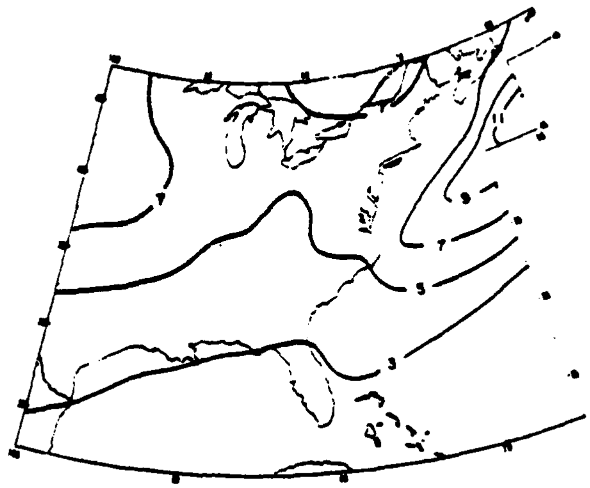


Figure 3. Standard deviations of the mean annual cyclone frequency for the years 1885-1978.

5. PRINCIPAL COMPONENTS ANALYSIS OF ANNUAL FREQUENCY DATA

5.1 The Analysis

Principal component analysis has successfully resolved the variance structure in multivariant, geophysical data (Kutzbach, 1967; Fritts et al., 1971; Resio and Hayden, 1975), and in terms of least square errors, this type of analysis provides a method for determining patterns in large data fields (Lorenz, 1956; Gilman, 1957; Kutzbach, 1967). The objective of the analysis is to isolate characteristic, recurrent, and independent modes of covariance among variables into a new set of independent variables. Basically, the analysis transforms a set of intercorrelated variables into a new coordinate system in which the axes are linear combinations of the original variates and are mutually orthogonal.

To prevent those grid cells with high mean cyclone frequencies (high latitudes) from dominating the total variance and consequently from dominating the eigenvector forms, the correlation matrix was used rather than the covariance matrix. The procedures for calculation of the eigenvectors follow those of Kutzbach (1967) and Vincent et al. (1976).

Principal component analysis provides a description of the major modes of variability in the data set. Typically, each component is identified with some property of the data field. The analysis also provides an index which measures the importance of each component within each year. Finally, the analysis provides an estimate of the total percent of variance in the data set which can be explained on the basis of each component.

5.2 The Eigenvectors

The percentage of variance and the cumulative percentage of variance explained by the first four eigenvectors is given in Table 1. As indicated in the table the first four eigenvectors account for 57.4% of the total variance. The problem has thus been reduced from a 74 variable

problem in which the variables are intercorrelated, to a 4 variable problem in which each new variable is orthogonal and thus statistically independent. Higher order eigenvectors explained smaller fractions of the total variance and are not dealt with here.

Eigenvector Number	% Variance Explained	Cumulative % Variance Explained
1	28.0	28.0
2	17.3	45.3
3	6.6	51.9
4	5.5	57.4

Table 1. The percentage of the total variance and cumulative percentage of the total variance of annual cyclone frequencies associated with eigenvectors 1-4. The values in column two are equal to the corresponding eigenvalue divided by the sum of all 74 eigenvalues.

The eigenvectors corresponding to the eigenvalues 1 through 4 are mapped in Figures 4, 5, 6, and 7. The first eigenvector (Fig. 4) indicates that the dominant mode of cyclone frequency variation about the mean is, with positive weightings, an abundance of cyclones over marine areas at the expense of cyclone frequencies over the continent. Years with negative weightings would be characterized by few cyclones over marine areas and above average frequencies over the continent. The corridor of positive values over marine areas shown in Figure 4 corresponds in location to the zone of increased cyclone frequencies found by Dickson and Namias (1976) and the east and south displaced storm track type identified by Resio and Hayden (1975).

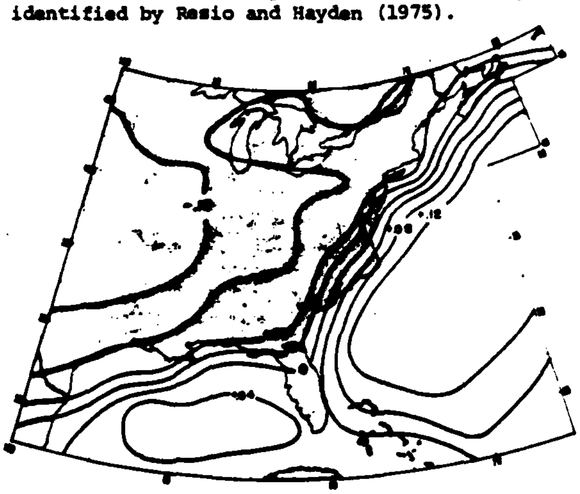


Figure 4. The first eigenvector of annual cyclone frequencies.

The second eigenvector (Fig. 5) has positive values over the entire field and as such indicates for positively weighted years, a general increase in cyclone numbers and in negatively weighted years, fewer than average cyclones. The dominant feature of the map of eigenvector no. 2 is the maximum centered over the coast of the mid-Atlantic. This pattern is rather similar to the chart of cyclogenesis frequency published by Petterssen (1941). This suggests that the second principal component might best be termed a coastal cyclogenesis function.

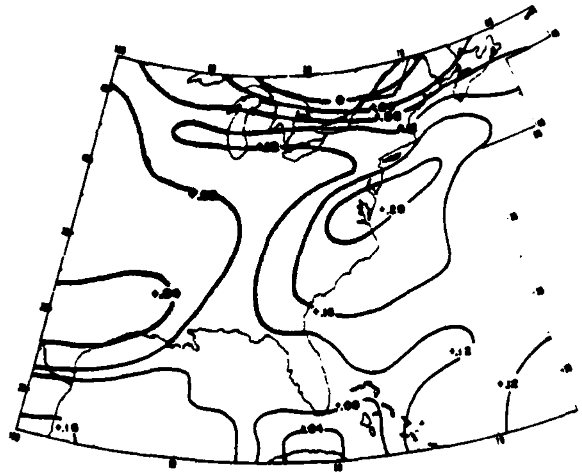


Figure 5. The second eigenvector of annual cyclone frequencies.

The third eigenvector (Fig. 6) contrasts storms tracking eastward from the Great Plains up the Ohio Valley and exiting the coast between Cape Hatteras and Cape Cod, with frequent cyclones in the Gulf Coast region.

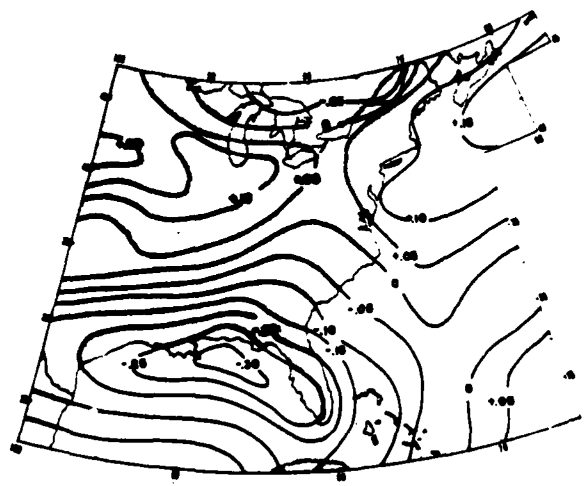


Figure 6. The third eigenvector of annual cyclone frequencies.

The fourth eigenvector (Fig. 7) contrasts the frequent cyclone occurrence in the Great Lakes-Saint Lawrence River region with cyclones out of the Great Plains. In years with positive weightings, storms are more frequent than average in southern Canada. Negatively weighted years show an increase in storm frequency in the Colorado storm track area.

The first four eigenvectors of annual cyclone frequencies constitute four new orthogonal axes which account for nearly 60% of the variance in the original data. In general, weightings on these four vectors for the 94 individual years of record varied from -10 to +10.

The meanings of each of the four new axes are summarized in Figure 8.

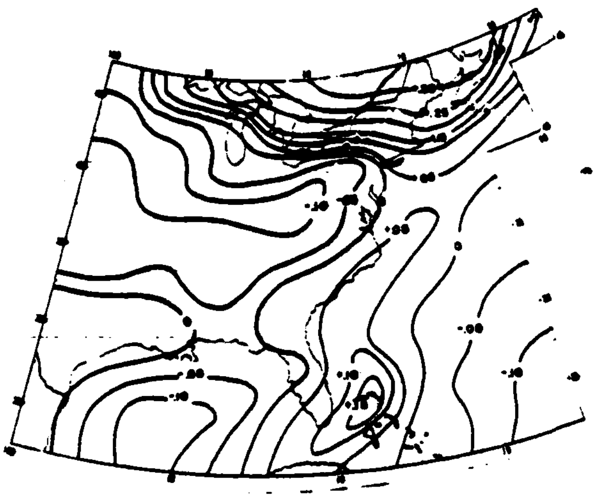


Figure 7. The fourth eigenvector of annual cyclone frequencies.

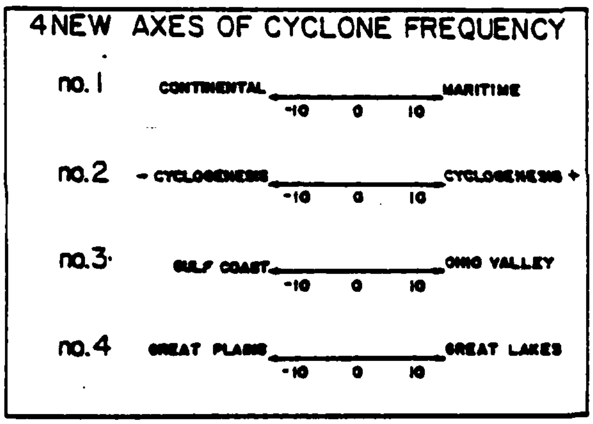


Figure 8. Summarization of the locations of cyclone numbers in excess of the mean for each of the first four eigenvectors. The - sign and the + sign associated with cyclogenesis for axis no. 2 indicates below and above normal cyclone numbers in the region of coastal cyclogenesis along the U.S. mid-Atlantic Coast.

5.3 <u>The Time Series</u>

The time series of eigenvector weightings for each year (1885-1978) for each of the first four eigenvectors is shown in Figures 9, 10, 11, and 12. The annual weightings of the first eigenvector show a broad quasi-sinusoidal variation of period slightly greater than 100 years. This variation thus suggests that cyclone frequencies declined over marine areas and increased over the continent between 1885 and 1925. Since 1925 cyclone frequencies over marine areas have increased and frequencies over the continent have declined. With the limited time series length it is not possible to establish whether the variation is indeed periodic.

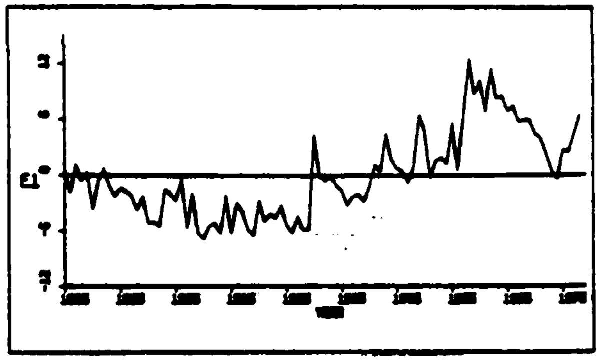


Figure 9. Time variation of the annual weightings of the first eigenvector (E_1).

Annual weightings of the second eigenvector (Fig. 10) also exhibit a century-long scale of variation from negative values at the beginning of the time series to positive values after 1910 and apparently back to negative values around 1960. If the interpretation of eigenvector 2 as representing coastal cyclogenesis is correct, then there should have been an increase in coastal cyclogenesis during the first five decades of the 20th century. This observation is supported by Resio and Hayden (1975) who show an increase in cyclogenesis along the mid-Atlantic coast.

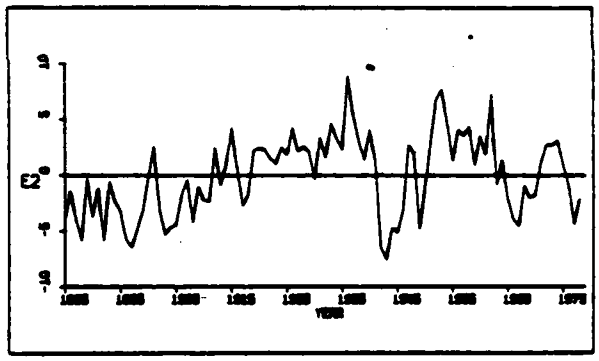


Figure 10. Time variation of the annual weightings of the second eigenvector (E_2).

The time series of the third and fourth eigenvectors (Fig. 11 and Fig. 12) show excursions from positive to negative weightings over shorter periods of years. The third eigenvector runs from negative values to positive values between 1900 and 1925, 1925 and 1950, and between 1955 and 1978. Spectral analysis shows some concentration of spectral power at about 23 years. The fourth eigenvector shows a broad decline from positive values in the early part of the record to low values in the late 1940's. Since the late 1940's weightings have again increased.

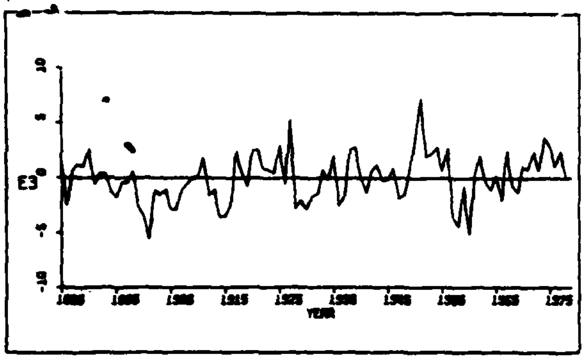


Figure 11. Time variation of the annual weightings of the third eigenvector (E_3).

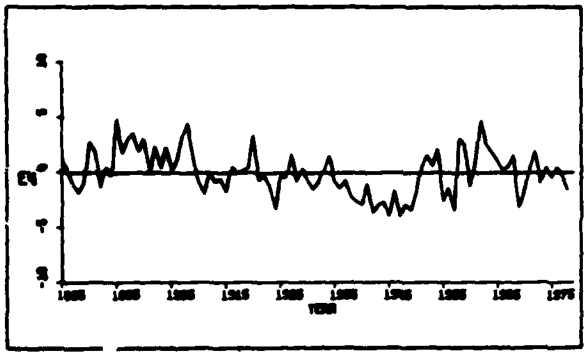


Figure 12. Time variation of the annual weightings of the fourth eigenvector (E_4).

6.0 DISCUSSION AND CONCLUSION

The variance in cyclone frequency is maximum off the U.S. Atlantic Coast. Much of this variance is due to the eastward displacement of storm tracks that parallel the coast and to cyclogenesis along the mid-Atlantic portion of the east coast. Both of these two contributions to the total variance exhibit century-long secular variation. These changes are undoubtedly due to changes in the intensity of the east coast baroclinic zone and to shifts in the North American long-wave location associated with blocking in the high latitudes as suggested by Resio and Hayden (1975) and Dickson and Namias (1976).

It thus appears that the increased storminess of the U.S. east coast since the early 1940's (Mather et al., 1964; Bosserman and Dolan, 1968; Hayden, 1975; Resio and Hayden, 1975; Dickson and Namias, 1976) is part of a secular variation of longer time scale.

ACKNOWLEDGMENT

This work was supported by a grant from the Office of Naval Research (Contract N000-14-75-C-0480).

REFERENCES

Bosserman, K., Dolan, R., 1968: The frequency and magnitude of extratropical storms along the Outer Banks of North Carolina. National Park Service Technical Report 68-4, 58 pp.

Bruun, P., 1962: Tracing of material movement on seashores. Shore and Beach, vol. 30, 10-15.

Dickson, R., Namias, J., 1976: North American influences on the circulation of the North Atlantic sector. Monthly Weather Review, vol. 104, 1255-1265.

Dolan, R., Godfrey, P., Odum, W., 1973: Man's impact on the barrier islands of North Carolina. American Scientist, vol. 61(2), 152-162.

Dolan, R., Hayden, B., Rea, C., Heywood, J., 1979: Shoreline erosion rates along the middle Atlantic coast of the United States. Geology (in press).

Fritts, H., Blasing, T., Hayden, B., Kutzbach, J., 1971: Multivariate techniques for specifying tree growth and climate relationships and for reconstructing anomalies in paleoclimate. Journal of Applied Meteorology, vol. 10, 845-864.

Gilman, D., 1957: Empirical orthogonal functions applied to thirty-day forecasting. Science Report No. 1, M.I.T., Department of Meteorology, 129 pp. (Available from CFSTI, U.S. Department of Commerce, Washington, D.C., AD117249).

Hayden, B., 1975: Storm wave climates at Cape Hatteras, North Carolina: recent secular variations. Science, vol. 190, 981-983.

Hoyt, J., 1967: Barrier island formation. Geological Society of America Bulletin, vol. 78, 1125-1136.

Klein, W., 1957: Principal tracks and mean frequencies of cyclones and anticyclones in the northern hemisphere. Research Paper No. 40, U.S. Weather Bureau, 1-53.

Kutzbach, J., 1967: Empirical eigenvectors of sea-level pressure, surface temperature and precipitation complexes over North America. Journal of Applied Meteorology, vol. 6, 791-802.

Lorenz, E., 1956: Empirical orthogonal functions and statistical weather prediction. Science Report No. 1, M.I.T., Department of Meteorology, 49 pp. (Available from CFSTI, U.S. Department of Commerce, Washington, D.C., AD110268).

Mather, J., Adams, H., Yoshioka, G., 1964: Coastal storms of the eastern United States. Journal of Applied Meteorology, vol. 3, 693-706.

Miller, J., 1946: Cyclogenesis in the Atlantic coastal region of the United States. Journal of Meteorology, vol. 3., 31-44.

Petterssen, S., 1941: Cyclogenesis over southwestern United States and the Atlantic coast. Bulletin of the American Meteorological Society, vol. 22, 269-270.

Petterssen, S., 1950: Some aspects of the general circulation of the atmosphere. Centenary Proceedings of the Royal Meteorological Society, 120-155.

Reed, R., 1960: Principal frontal zones of the northern hemisphere in winter and summer. Bulletin of the American Meteorological Society, vol. 41, 591-598.

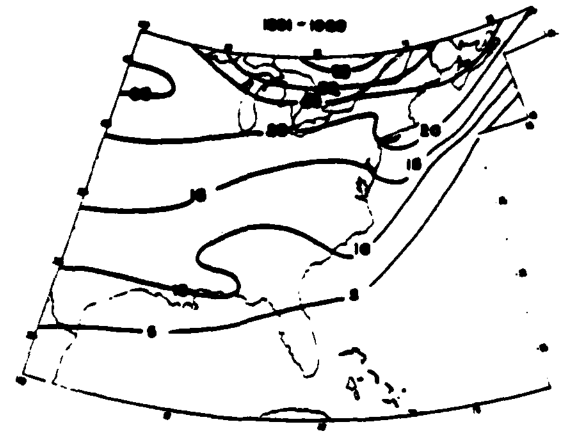
Resio, D., Hayden, B., 1975: Recent secular variations in mid-Atlantic winter extratropical storm climate. Journal of Applied Meteorology, vol. 14, 1223-1234.

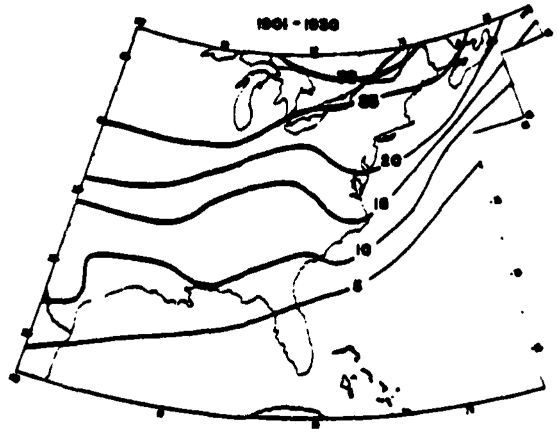
U.S. Army Corps of Engineers, North Atlantic Division, 1971: National Shoreline Study. U.S. Army Engineer Division.

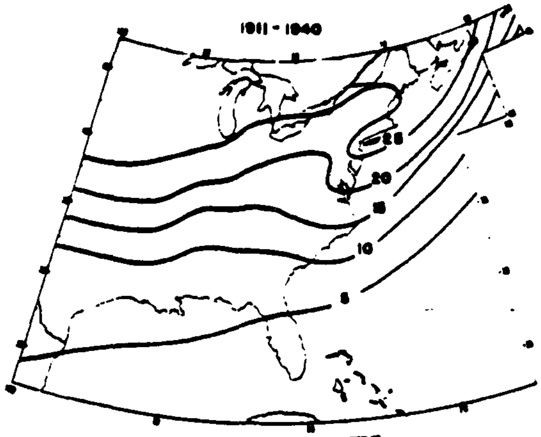
Vincent, L., Dolan, R., Hayden, B., Resio, D., 1976: Systematic variations in barrier island topography. Journal of Geology, vol. 84, 583-594.

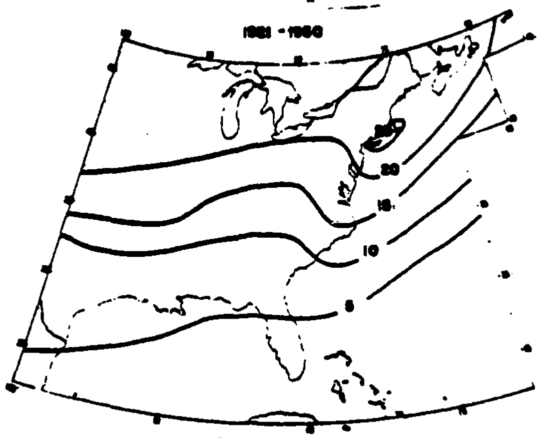
APPENDIX

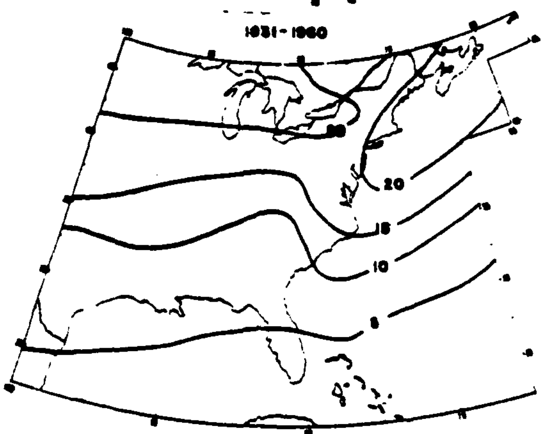
The secular variations in cyclone frequencies over Eastern North America and the Western North Atlantic are sufficiently pronounced that they are evident in charts covering 30 years. The charts following cover the thirty-year periods between 1891 and 1970.

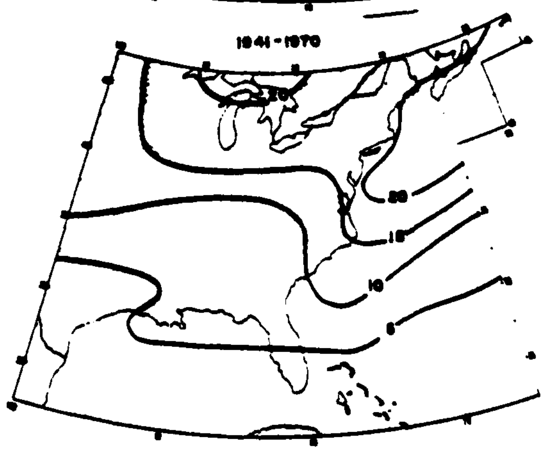












Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Department of Environmental Sciences
University of Virginia
Charlotttesville, Virginia 22903

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

Unclassified

3. REPORT TITLE

Atlantic Coast Extratropical Cyclones: Characteristic Frequency Patterns and their Secular Variation

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

Bruce Hayden

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1980	6	20

8a. CONTRACT OR GRANT NO.

N00014-81-K-0033

b. PROJECT NO.

NR 389 170

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

Technical Report No. 21

9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

Reprinted from Preprint Volume Second Conference on Coastal Meteorology, Jan. 30-Feb. 1

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

To examine the spatial and temporal variations in cyclone frequency the eigenvectors of annual cyclone frequencies (1885-1978) were calculated. Two century-long secular variations are found. The increased storminess along the U.S. Atlantic coast of the last several decades is shown to be part of a longer period variation.

Unclassified

Security Classification

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cyclones						
Storms						
Extratropical						
Climate						
Climate change						
Atlantic Coast						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Unclassified
Security Classification

Technical Report No. 22

SEASON-TO-SEASON CYCLONE FREQUENCY PREDICTION

Bruce Hayden

Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

June 1980

Geography Programs
Office of Naval Research
Contract No. N00014-81-K-0033

Season-To-Season
Cyclone Frequency Prediction

Bruce P. Hayden
Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

June 1980

ABSTRACT

Winter and summer cyclone frequencies for eastern North America and the western North Atlantic were tabulated for 2.5° latitude by 5° longitude grid cells for the years 1885-1979. Correlation matrix eigenvectors were calculated for matrices of both the winter and summer data. The first four eigenvectors of each matrix are highly similar in form and the first, second and fourth eigenvectors are highly correlated in the time domain. These correlations permit a season-in-advance estimation of cyclone frequencies. The multivariate prediction model developed is called the University of Virginia Climate Prediction Model. Forecast skill in both winter and summer averages 66% relative to the means as forecasts. Forecast failure (negative skill) occurs in about 8 percent of the winter forecasts and 11 percent of the summer forecasts. Positive skill relative to chance and persistence is also demonstrated.

1. Introduction

In 1914, C.J. Kullmer proposed that cyclone frequency patterns for North America were in part determined by the motions of sunspots on the solar surface and were thus predictable to a degree. Kullmer's subsequent work (1933, 1943) further substantiated his claims. Ellsworth Huntington (1914a, 1914b) publicized Kullmer's ideas as the "Solar Cyclonic Hypothesis." The Solar Cyclonic Hypothesis has since fallen into obscurity but the goal of long-range climate prediction has been codified in the National Climate Program. In this report a method for season-in-advance cyclone frequency prediction is detailed. The multivariate statistical model developed is referred to here as the University of Virginia Climate Prediction Model.

2. Earlier Work

a. Cyclone Frequencies

The movements of the centers of cyclones have been charted for North America since 1873. Systematic study of the climatology of cyclones began in the 1890s with the work of Bigelow (1897) on "storms, storm tracks and weather forecasting." Shortly after the turn of the century two groups began detailed studies of cyclones and cyclone movements. Bowie (1906) and Bowie and Weightman (1914) studied the frequency of cyclones geographically and classified the cyclones by origin and movement in order to improve weather forecasting. The other group, Kullmer

(1914) and Huntington (1914a, 1914b), studied covariations in the record of sunspots and cyclone frequencies in order to achieve long-range cyclone frequency prediction. Bowie and Weightman's work has stood the test of time. Shortly thereafter Bjerknes (1918) deduced the three-dimensional structure of moving cyclones and with Solberg (Bjerknes and Solberg, 1922) published a paper on the life cycle of cyclones and the theory of the polar front. In contrast, physical mechanisms linking sunspots and terrestrial cyclones have eluded investigators and although Kullmer (1933, 1943) updated his analyses of cyclone frequencies, we are no nearer to the predictive capacity he envisioned.

Interest in and appreciation of the significance of the climatology of cyclones was revived during and after World War II (Petterssen, 1941; Weightman, 1945; Miller, 1946; Miller and Mantis, 1947; Saucier, 1949; James, 1952; Hurley, 1954). This work culminated with Klein's (1957, 1958) detailed studies of spatial distribution of cyclone frequency and Hosler and Gamage's (1956) determination of the secular history (1905-1954) of cyclone frequencies.

During the 1960s attention shifted to the marine sector. Mather, Adams and Yoshioka (1964) and Mather, Field and Yoshioka (1967) summarized the climatology of damaging Atlantic coast cyclones and reported a secular change toward more frequent damaging storms caused by lowering of the average central pressure of storms off the Atlantic coast. More recently, Zishka and Smith (1980) reported a general trend of lower central

pressure for cyclones over the North American sector. Hayden (1975), Resio and Hayden (1975), and Hayden (1980a) confirmed the trend over the last five decades toward more frequent and more intense cyclones off the U.S. Atlantic coast. For the Atlantic coastal region a shift in the mean path of movement of cyclones has been documented (Resio and Hayden, 1975; Dickson and Namias, 1976; Hayden, 1980a).

In the last few years improved climatological assessments of cyclone frequencies have entailed more extensive and intensive grids for sampling (Reitan, 1974, 1979; Zishka and Smith, 1980) and more extensive historical coverage of cyclone frequency data fields (Hayden, 1980a).

b. Climate Prediction

The predictability of climate is conditional on establishing and having foreknowledge of forcing processes, e.g. sunspots (Kullmer, 1943), chandler motions of the Earth's axis of rotation (Bryson and Starr, 1977), sea surface temperature fields and atmospheric circulation (Namias, 1974), analog climate states (Barnett and Preisendorfer, 1978) or establishing the existence of seasonal or longer climatological persistence such as identified by Sir Gilbert Walker and E.W. Bliss (1932) and employed in the present study. Resolving the causes of climatological persistence and its occasional failures returns one to the issue of climate-forcing processes.

c. Multivariate Statistical Prediction Models

Early use of multivariate techniques in prediction have focused on prediction of prehistoric atmospheric conditions from modern data. Fritts et al. (1971) used canonical correlations between patterns of hemispheric pressure and patterns of tree-ring growth to extend (synthesize) backward pentad mean seasonal pressure charts to 1700. In similar fashion Webb and Bryson (1972) used multivariate statistics to reconstruct precipitation, temperature and snowfall conditions during the Holocene in the upper Midwest from modern pollen and weather data and from fossil pollen stratigraphies. Similar procedures have been employed to predict (hindcast) sea surface temperatures at the end of the last ice age (18,000 BP) from plankton in sea floor cores (CLIMAP, 1976). Torranin (1972) used canonical correlation to predict hydrological conditions in the mountains of California from vector patterns of sea surface temperature in the North Pacific. Gilman (1957) used principal component analyses of pressure, precipitation and temperature fields to predict one variable from the others. In the current study, correlations between principal components of winter and summer cyclone frequency patterns define three modes of climatological persistence such that knowledge of the vector patterns of cyclone frequencies in one season permits estimation of frequency patterns in the following season.

3. The Data

Cyclone frequencies for winter (October - March) and summer (April - September) for the years 1885-1979 were tabulated for the 74, 2.5°-latitude by 5.0°-longitude grid cells comprising the study areas shown in Figure 1. From monthly charts of the "Tracks of the Centers of Cyclones at Sea Level" published by the *Monthly Weather Review* and in recent years by the *Mariners Weather Log*, seasonal totals of cyclones passing through each grid cell were recorded. Multiple entries of a given storm in a grid cell were ignored. The resulting data matrices have the dimensions of 74 grid-cell variables and 94 yearly cases. Frequencies were not adjusted for latitude variations in grid-cell area because of distortions involved in such adjustments (Hayden, 1980b).

4. Long-Term Means and Variances

Figure 2 shows the mean winter and summer frequency of cyclones per grid-cell for the period 1885-1979. The winter and summer patterns are similar in all respects except in magnitude. Cyclones are more frequent in winter. These seasonal mean frequency patterns are similar to the annual means shown by Hayden (1980a). In general cyclones increase with latitude and proximity to the east coast where a dominant frequency maximum axis is found. The location of this frequency maximum is perhaps associated with the dynamic affects of the Appalachian Mountains and baroclinic affects of the coastal zone.

The standard deviation of winter and summer cyclone frequencies is presented in Figure 3. Like the patterns of the means, the standard deviations for winter and summer are similar in form and bear great similarity to the annual pattern published earlier (Hayden, 1980a). The dominant feature of the chart is the pronounced frequency maximum off the Atlantic coast. The axis of this maximum is seaward of the maximum in the mean field (Fig. 2) and apparently rotated clockwise several degrees. The location of the standard deviation maxima closely approximates the locus of the Gulf Stream. The geographic relationship between the Gulf Stream and the variance maxima in cyclone frequencies is interesting in view of the season-to-season persistences detailed in subsequent sections. The standard deviations landward of the east coast are rather modest suggesting that the axis of storm occurrences may expand eastward, but in general not westward, of the Appalachians.

5. Principal Component Analyses of Winter and Summer Frequency Data

a. The Analysis

Principal component analyses have successfully resolved the variance structure in multivariate, geophysical data (Kutzbach, 1967; Fritts et al., 1971; Resio and Hayden, 1975; Hayden, 1980a), and in terms of least square errors, this type of analysis provides a method for

determining patterns in large data fields (Lorenz, 1956; Gilman, 1957; Kutzbach, 1967). The objective of the analysis is to isolate characteristic, recurrent, and independent modes of covariance among variables into a new set of independent variables. Basically, the analysis transforms a set of intercorrelated variables into a new coordinate system in which the axes are linear combinations of the original variates and are mutually orthogonal.

To prevent those grid cells with high-mean cyclone frequencies (high latitudes) from dominating the total variance and consequently from dominating the eigenvector forms, the correlation matrix was used rather than the covariance matrix. The procedures for calculation of the eigenvectors follow those of Kutzbach (1967) and Vincent et al. (1976).

Principal component analysis provides a description of the uncorrelated major modes of variation in the data set. Typically, each component is identified with some property of the data field. The analysis also provides an index which measures the importance of each component within each case. Finally the analysis provides an estimate of the total percent of variance in the data set which can be explained on the basis of each component. Separate principal component analyses were run for the winter and summer data matrices.

b. Significance of the Eigenvectors

Following the lead of Barnett and Preisendorfer (1978), 94 year-by-74 grid cell matrices of randomly selected (winter and summer) cyclone frequencies were prepared and subjected to eigenvector analyses. The percentage of variance explained

by each of the first 20 eigenvectors calculated as compared with the percentages of variance explained by the eigenvectors of actual winter and summer cyclone frequency occurrences is shown in Figure 4. For both winter and summer analyses the first 5 eigenvectors accounted for more variance than the first six "random" cyclone eigenvectors. Only the first four eigenvectors are studied in this report.

c. The Eigenvectors

The percentage of variance and the cumulative percentage of variance explained by the first four eigenvectors for the winter and summer seasons is given in Table 1. As indicated, the first four winter and summer eigenvectors account for 52 percent and 49 percent of the total variance, respectively. The problem has thus been reduced from two 74-variable problems in which the variables are intercorrelated, to two 4-variable problems in which each new variable is orthogonal and thus statistically independent. Higher order eigenvectors explained small fractions of the total variance and are not used in the model developed here.

The winter and summer eigenvectors corresponding to the eigenvalues 1 through 4 are mapped in Figures 5, 6, 7, and 8. The first eigenvectors of winter and summer analyses (Fig. 5) are

similar in form and amplitude and indicate that the dominant mode of cyclone frequency pattern variation about the mean is, with positive weightings, an abundance of cyclones over marine areas occurring at the expense of cyclone frequencies over the continent. Years with negative weightings, in both winter and summer, would be characterized by fewer than average cyclones over marine areas and above average frequencies over the continent. Using annual data it was shown that this pattern is not the result of poor cyclone identification over marine areas (Hayden, 1980a).

The second eigenvectors of the winter and summer data matrices (Fig. 6) have positive values over the entire field and as such indicate, for positively-weighted years, a general increase in cyclone numbers and in negatively-weighted years, fewer than average cyclones. The dominant feature on the maps of the second eigenvectors is the maximum centered over the coast of the mid-Atlantic. This pattern is rather similar to the chart of cyclogenesis frequency

published by Petterssen (1941). As was the case with the first pair of eigenvectors, the second eigenvectors are essentially the same in form and amplitude. There is no indication of seasonal differentiation.

The third eigenvector in both winter and summer (Fig. 7) contrasts storms tracking eastward from the Great Plains up the Ohio Valley and exiting the coast between Cape Hatteras and Cape Cod, with frequent cyclones in the Gulf coast region. Again no seasonal differentiation is evident.

The fourth eigenvectors (Fig. 8) contrast the frequent cyclone occurrence in the Great Lakes-Saint Lawrence River region with cyclones out of the Great Plains. In years with positive weightings, storms are more frequent than average in southern Canada. Negatively-weighted years show an increase in storms along the Colorado storm track.

The first four eigenvectors of the winter and summer cyclone frequency matrices constitute four pairs of new, orthogonal variables that account for about 50 percent of the variance in the original data sets. These new variable pairs are functionally similar in form and amplitude. There is no evidence of seasonal differences in the patterns. The four vector pairs closely resemble vectors calculated from an annual data matrix published earlier (Hayden, 1980a).

d. The Time Series

The time series weightings of each of the four eigen-vector pairs for each year (1885-1979) are shown in Figure 9. The annual weightings of the first eigenvectors in winter and summer show broad, quasi-sinusoidal variation of period

slightly greater than 100 years. This variation suggests that in both winter and summer, cyclone frequencies declined over marine areas and increased over the continent between 1885 and 1925. Since 1925, cyclone frequencies over marine areas have increased and frequencies over the continent have declined. Visual inspection of Fig. 8A for winter and summer indicates covariations at both high and low frequencies.

Annual weightings of the second winter and summer eigenvectors (Fig. 9) also exhibit century-long scales of variation from negative values at the beginning of the time series to positive values after 1910 and back to negative values around 1960. If the interpretation of the second eigenvectors as representing coastal cyclogenesis is correct, then there should have been an increase in coastal cyclogenesis during the first five decades of the 20th century. This observation is supported by Resio and Hayden (1975) who show an increase in cyclogenesis along the mid-Atlantic coast. The second eigenvector time series for both winter and summer (Fig. 9) also shows remarkable similarities to Reitan's (1974) tabulations of total cyclone numbers for the western part of the Northern Hemisphere. As was the case with the first eigenvector pairs, both high and low frequency covariations are evident.

The time series weightings for third and fourth eigenvector pairs (Fig. 9) also show winter-summer similarities. To quantify the similarities between the first four eigenvector weightings for the winter and summer time series, correlation coefficients were calculated for both winters

versus the following summers and for summers versus the following winters. These correlation coefficients are summarized in Table 2. Clearly there are at least three synoptic scale modes of seasonal persistence evident from these analyses. Given the essential identity between the winter and summer eigenvector pairs and the significant correlation between their respective time series, a predictive model can be constructed and evaluated using the first, second and fourth eigenvectors.

6. The University of Virginia Climate Prediction Model

a. The Predictive Equations

The cyclone frequency values at each of the 74 grid cells (Fig. 1) for a given winter (C_w) may be estimated from the following:

$$C_w = \bar{X}_w + a^*_{1w}\ \sigma_w\ E_{1w} + a^*_{2w}\ \sigma_w\ E_{2w} + a^*_{4w}\ \sigma_w\ E_{4w}$$

where $\bar{X}_w$ is the matrix of 74 long-term (1885-1979) mean winter cyclone frequencies (Fig. 2); σ_w is the standard deviation matrix of $\bar{X}$ (Fig. 3); E_{iw} are the four winter eigenvectors (Figs. 5, 6, 7, and 8); and a^*_{iw} are the predicted eigenvector weightings. The a^*_{iw} are calculated from regressions between the winter and summer eigenvector weighting time series (Fig. 9) and the eigenvector weightings for the summer preceding the winter forecasted. A similar equation is structured for the prediction of summer cyclone frequency patterns. In short this forecast method states that the cyclone frequency pattern for the coming season should be

similiar to the average for that season with the addition of three persistence components based upon the occurrence of cyclones during the preceding season. With the University of Virginia Climate Prediction Model, a forecast of cyclone frequencies is produced for each 2.5°-latitude by 5.0°-longitude grid cell of the study area (Fig. 1). The cyclone frequency forecast for each grid cell can be compared to the actual cyclone occurrence and forecast skill can be quantified.

b. Model Evaluation

In order to evaluate the predictive utility of the University of Virginia Climate Prediction Model, test forecasts were made using independent data. From the total of 94 years of winter and summer data available, every ten years were removed from the data matrix. The new smaller winter and summer matrices of 74 variables and 84 cases were subject to principal component analyses. The eigenvectors derived and the weightings for each season were calculated and regressed against the previous season. The eigenvector weightings for summer were used to estimate the weightings for the following winter and vice versa. The forecasted weightings were then applied to the predictive equations and a cyclone frequency forecast was produced. The ten independent years of data were then returned to the matrix and a new set of independent years was removed, the model was rebuilt, and a second forecast was produced. This was repeated until all 94 years of

record were predicted for both winter and summer. While this method of selection of independent data is an adequate test it differs from prediction of the next ten years (1980s). To approximate this forecast situation, the 1970s were removed from both the winter and summer data matrices. The models and predictive equations were reformed and each year was forecast in turn. On completion of these forecast exercises, the results were compared to historical occurrences and forecast skill was calculated.

c. Predictive Skill

Numerous methods have been advanced to quantify estimates of forecast skill (Brier and Allen, 1951; Vernon, 1953) and as noted by Brier and Allen the method selected depends on the purpose of verification. The purpose here is twofold. First, it is essential to establish the relative level of reliability of the University of Virginia Climate Forecast Model and secondly, identify forecast errors and determine their nature and possible cause. The basic test of forecast skill employed here is the percent of correct forecasts (percent skill score) relative to the use of the climatological mean as a forecast. Thus while the model provides a numerical value of cyclone frequency, the skill test used here evaluates only the accuracy of forecasts of the form greater or less than the mean. For comparison, Heidke skill scores, absolute errors of the forecast, root mean square errors of the forecast, deviation skill score and quadratic skill scores were also calculated and will be summarized.

For each season of each of the 94 years forecasted the forecast cyclone frequency at each grid cell was compared to the actual occurrence of cyclones and the long-term mean frequency. The percentage of the 74 grid cells was calculated for each season and year where the model provides a better estimate of actual cyclone occurrences than the mean. This aggregate skill is referred to here as global skill following Barnett and Preisendorfer (1978). The average (1885-1979) percent skill score was also determined for each grid cell for each season and is referred to as local skill.

d. Global Skill

Figure 10 gives the grid average (global), percent skill scores for season by each year. The average percent skill score for the 94 years is 66 percent for both winter and summer season predictions. Frequency histograms of yearly global skill scores by 5 percent class intervals are given in Figure 11. The distribution of percent skills is near normal. For winter forecasts, 92 percent of the years forecasted had positive skill while 87 percent of the summer forecasts had positive skill. All years with negative global forecast skill were isolated for additional study (skill was calculated for only the first half of the season forecasted). Half of the failure years were found to have positive forecast skill for the first three months and percentage improvements in forecast skill were achieved for 92 percent of the original forecast failures.

The population of forecast failure years was also subjected to a new model construction. In this exercise only the actual cyclone occurrences in the latter half of the antecedent season were used to derive the forecast of the subsequent season. Again about half of the failure years re-forecasted showed positive skill. These tests indicated that major, mid-season change in the general circulation cause forecast failure in the subsequent season and that general circulation changes within a season are a frequent cause of failure to achieve positive forecast skill for that season.

The average percent skill for winter and summer as compared with Heidke skill scores (Heidke, 1926), absolute errors and root mean square errors (RMSE), deviation skill and quadratic score (Vernon, 1953) are given in Table 3. As noted by Serfling (1975) "statistical models for meteorological phenomena typically perform poorly in extremes." When all 94 years forecasted are considered, that is the case here. The quadratic and deviation skill scores penalize failure to predict extremes. With the deviation skill score, the penality of incorrect forecasts increases linearly with increasing departure from the mean and for the quadratic skill score the penality increases as the square of the departure from the mean. Figure 12 illustrates the relationship between global percent

skill scores and quadratic skill scores for the 94 summer predictions and the 94 winter predictions. When both the percent and quadratic skill scores are positive, the two measures are linearly related. There is no apparent relationship between percent and quadratic skill score when only cases with negative quadratic skill scores are considered. It seems clear that the model being tested here does a good job, in general, predicting the form or pattern of departure from the mean and when forecast skill is positive a good job of predicting magnitude of the departures from long-term averages.

While the procedure of selecting test years from within the data record is an independent test, questions still remain about extension of the forecast into the future. With the 1970s removed from the data record the model was rebuilt and the winter of 1969-1970 and summer of 1970 were predicted and percent skill scores were calculated. The 1970 year was then added back to the data matrix, the model was rebuilt and the next winter and summer were predicted. Each year of the 1970s was computed in this manner in an effort to mimic a real forecast situation. In Figure 13 the resulting global percent skill scores for each year are compared with those given in Figure 10. Heidke deviation and quadratic skill scores are also shown. In both winter and summer the forecast skill is about

the same as that calculated from within the data record. The model thus is equally good in forecasting into the future. Figure 14 compares the global percent skill scores for the forecast of the 1970s with the quadratic, deviation and Heidke global skill scores. The various scores parallel each other. This seems consistent with the data shown in Figure 12. Figure 12 clearly suggests that when the global percent skill score is high both the global quadratic and deviation skill scores are also high. When global percent skill score falls below 50 percent the quadratic and deviation skill scores become negative. These results suggest that, contrary to Serfling's (1975) dictum about statistical models' general failure to predict extremes, the University of Virginia Climate Prediction Model does a good job of predicting extreme values when a positive percent skill is achieved.

e. Local Skill

Figure 15 shows the geographic variation (local skill) of forecast skill for winter and summer. In both charts, positive skill is found for all grid cell locations. (Histograms of winter and summer grid-cell percent skill scores by 5 percent class intervals are given in Figure 15.) In general, winter forecasts have a greater range of percent skill about the chart mean of 66 percent than does summer. The isopleth field for winter is also more highly organized than the summer field.

f. Long-term versus short-term global skill

The time series of eigenvector weightings (Fig. 9) exhibit long-term trends, i.e. year-to-year and longer persistences. Inspection of Figure 9 also reveals numerous winter-summer synchronous departures from the general trends. Third-order polynomial curves were fitted to the time series of eigenvector weightings . using a least square criterion. The polynomial curves were then subtracted from the original time series. The time series of polynomial departures (PD) were correlated with the time series of global skill (S) for the following season. These correlations are summarized in Table 4. With negative correlations, global skill declines with increasing departures from the polynomial trend and indicates a dominance of long-term persistence in the predictions. With positive correlations, global skill increases with increasing departures from the trends indicating high frequency (short-term) contributions to overall skill. Table 4 indicates, however, that strong positive and negative correlations are not found and thus there is no dominance of high or low frequency persistences in the skill achieved. Even if the correlations were more robust and significant, the slopes on the regression are modest (Table 4). For example, use of the polynomial curve of eigenvector number 1 weightings rather than the actual weightings would net a potential skill improvement of about 2.6 percentage points. In similar fashion, using

just the departures from the polynomial trend for eigenvector 4 would net a potential skill improvement of 4 percentage points. Unfortunately the correlations are weak and we must conclude that the skill achieved with the University of Virginia Climate Prediction Model is the result of both long- and short-term persistences in the eigenvector weightings.

g. Forecast Skill Relative to Chance, Persistence and the Previous Season as a forecast.

In earlier sections skill was assessed relative to the long-term mean (1885-1979). Here, the skill achieved relative to chance, persistence, and the previous season as forecasts is evaluated. In each of these computations of forecast skill a 94 year-by-74 grid cell matrix of winter and summer cyclone frequency was prepared as a base of comparison. The cyclone frequency matrix of random (chance) values was discussed in an earlier section.

The matrices for the test of skill relative to persistence were constructed from the actual data. Third-order polynomials were fitted to the 94 year time series for each of the 74 grid cells for both the winter and summer data. From the 148 polynomial curves, values for each grid cell for each year and season were extracted. The resulting winter and summer matrices were used in the persistence tests for model skill.

The simplest forecast to test model skill against is that the coming season will be like the previous season. Unfortunately cyclone frequencies are higher in all grid cells in winter than summer. To make adjustments for this seasonal difference, the winter matrix was multiplied by the ratio of the summer to winter long-term means for each grid cell. The summer matrix was

multiplied by the ratio of winter to summer long-term means. In short, the winter of 1978-79, when adjusted to summer frequency levels, becomes the forecast for the summer of 1979.

The University of Virginia Climate Prediction Model achieves a higher level of skill than the mean, chance, persistence or the previous season as a forecast (Table 5). Skill relative to persistence shows the most modest gains. This is not surprising because the model is basically a persistence forecast system. Based on the results summarized in Table 5, it apppears that about two-thirds of the skill is due to long-term persistence and about one-third to shorter-term persistence. The previous season, however, is not a very good forecast of the season which follows. Lag regressions of the time series shown in Figure 9 suggest that model skill for the time interval near or slightly longer than 1 year may be better than the 6-month seasons studied here. The deviation and quadratic skill scores are negative for the model relative to persistence. This results because of the higher number of failure years using this most stringent base of comparisons (see Figure 12). Most of the years with a percent skill score of 60 or higher for the test of skill relative to persistence had positive deviation and quadratic skill scores.

The only winter/summer disparity in skill scores comes from comparison of model skill achieved with the previous season as a prediction. Apparently summers are not as good as estimators of the following winter as visa versa. Or put more directly, the character of winter more frequently extends over to summer than does summer to winter.

h. The Winter of 1979-1980

The first "future" forecast made using the University of Virginia Climate Prediction Model was for the winter of 1979-1980. The forecast was completed in November of 1979 and has been verified. Percent, Heidke, deviation and quadratic skill scores were 84 percent, .68, .18, and .33 respectively. The reduction in the root mean square error of the forecast, relative to the mean as a forecast, was .56 cyclones per grid cell. The reduction in the absolute error of the forecast relative to the mean was 0.44 cyclones per grid cell. Figure 17 shows comparisons of the 1979-1980 predicted and actual cyclone frequencies, the difference between the predicted and the long-term mean and the difference between the actual and mean frequencies, and the difference between the actual occurrences and the predicted occurrences. Forecast skills are also listed in Figure 17. Twelve of the 74 grid cells were not forecasted correctly (Figure 14E). For example, at 37.5°N, 97.5°W fewer storms than normal were predicted and fewer than normal occurred; the cyclone frequencies at this location were 4.74 fewer than predicted. The anomaly was under-estimated at 37.5°N, 67.5°W where more than average cyclone numbers were predicted, and more than normal occurred. The anomaly at this site was also

underestimated. Overall forecast skill for the 1979-1980 winter was very good.

7. Discussion and Conclusion

The University of Virginia Climate Prediction Model provides a forecast of cyclone frequency patterns for eastern North America and the western North Atlantic. For both winter and summer, area average percent forecast skill scores are 66 percent. Geographically the model shows positive forecast skill in all areas and as expected forecast skill varies in both space and time. The model essentially produces a prognostic chart of the expected spatial cyclone frequency distribution (Fig. 17). The interpretation of these charts in terms of warmer and cooler and wetter and drier regions requires additional study. Schematic models such as those suggested by Klein (1948) should prove particularly useful as chart interpretation aids. In addition, statistical pattern analysis methods (Blasing, 1975; Kutzbach, 1967; Fritts et al., 1971) and robust data collections should permit the product of the University of Virginia Climate Prediction Model to derive second order models. For example, preliminary study indicates that the yearly weightings of the first eigenvector of cyclone frequencies are highly correlated with heating degree day departures from the historical trend line for Washington, D.C., and is also highly correlated with the frequency of one inch or greater snowfalls in Richmond, Virginia.

Considerable study is required to evaluate the reliability and value of such derived forecasts.

The University of Virginia Climate Prediction Model is a persistence forecast system. During the early phases of this investigation the discovery of season-to-season components of persistence in the fields of cyclone frequencies was rather surprising. Aside from the early work of Sir Gilbert Walker and E. W. Bliss (1932) and a few scattered reports, the literature is depauperate in citations on seasonal persistences of atmospheric properties. Those seasonal persistences which are reported are generally of synoptic scale or larger. Namias (1960) refers to "contrasting 'regimes' on the order of a month, in which weather processes persistently recur," and Ballenzweig (1959) notes that over a period of a month or a season, "it is frequently found that the tracks of tropical cyclones cluster about certain preferred axes." Namias, Dunn and Simpson (1955) refer to this cluster about a preferred axis as a "closely knit family." It is clear that persistence in the movement of cyclones within a season has been observed and this is visually born out in inspections of the monthly charts of the centers of cyclones. What is less clear and more important is the physical basis for the observed persistence.

Some clues as to the physical basis for cyclone frequency pattern persistence can be derived from the charts of means and variances (Figs. 2 and 3). In Figure 2, a pronounced frequency minima is evident along the Appalachian

Mountains. Colucci (1976) in a high spatial resolution cyclone study of the region confirms this frequency minima. Colucci also notes, however, that cyclone deepening over the Appalachians is also typical. It would appear then that the Appalachians exert dynamic, albeit temporally constant, effects on cyclone frequency patterns. The maximum frequencies in the mean field (Fig. 2) closely parallel the coast, also a static feature. The maximum in the variance field (Fig. 3), however, is not congruent with the means. The variance maximum closely parallels the Gulf Stream. Colucci (1976) notes that 1) storms concentrate along the northern edge of the Gulf Stream; 2) deepening is favored along the coast and along the northern edge of the Gulf Stream; and 3) that winter precipitation along the Atlantic coast may be modulated by water temperatures between the Gulf Stream and the coast. The position of the Gulf Stream, the strength of the baroclinic zone along its northern edge and the strength of the baroclinic zone along the coast all vary in time. Harrison et al. (1965) reports that coastal erosion at Virginia Beach is most highly correlated with water temperatures. This is due to the presence of storms offshore (along the Gulf Stream) and the high waves they produce which in turn erode the beach, mix the water column and advect cold waters southward along the coast. In studies at the University of Virginia we have found that the frequency maximum of cyclogenesis along the coastal baroclinic

zone lags behind the frequency maximum of storms moving along the Gulf Stream (Resio and Hayden, 1975). The intensity of the coastal baroclinic zone may be modulated by the movement of storms along the Gulf Stream, and by shifts in the Gulf Stream and eddies along its margins.

The winter geography of snowcover over North American and Pacific Ocean sea surface temperatures may also contribute to the persistence of cyclone frequency patterns. In fact, given the multiplicity of potential causes of persistence, it is not surprising that several statistically independent modes of cyclone frequency persistence exist.

Persistence forecasting is well within the tradition of forecast method and technique and it is generally recognized that persistence eventually fails. Failure (negative skill) using the University of Virginia Climate Prediction Model occurs about 8 percent of the time for winter forecasts and 12 percent for the summer. Failure may occur because the year forecasted is near the mean pattern or because circulation patterns change, sometimes abruptly (Namias, 1960). The causes of the circulation change are more obscure. Additional research on seasons with negative forecast skill is required before the forecast system could be applied with equal confidence in all years.

Preliminary analyses indicate that forecast skill can be improved by multiple regression models for predicting eigenvector weightings. These analyses also suggest that forecast skill will be maximum for forecasts slightly

longer than 1 year in advance. New models for these improvements and for an enlarged geographic area of coverage are being constructed and evaluated and will be reported in due course.

8. Acknowledgments

The research presented here was supported by the Office of Naval Research Coastal Science Division (N00014-75-C-0480). Phyllis Ross and Stephanie Lent were invaluable during the data collection phase of this work. Stephanie Lent and Bill Smith provided computer support. Reviews and constructive suggestions were kindly provided by Robert Dolan, Reid Bryson, Jerome Namias, Patrick Michaels, Robert and Joanne Simpson and Michael Garstang. Their guidance has substantially improved this paper.

REFERENCES

Ballenzweig, E.M., 1959: A practical equal-area grid. J. Geophys. Res., 64(6), 647-651.

Barnett, T.P. and R.W. Preisendorfer, 1978: Multifield analog prediction of short-term climate fluctuations using a climate state vector. J. Atmos. Sci., 35(10) 1771-1787.

Bigelow, F.H., 1897: Storms, storm tracks, and weather forecasting. U.S. Weather Bur. Bull., 20(114), 87 p. Washington, D.C.

Bjerknes, J., 1918: On the structure of moving cyclones. Geof. Pub., 1(2), 1-8.

------and H. Solberg, 1922: Life cycle of cyclones and the polar front theory of atmospheric circulation. Geof. Pub., 52(1).

Blasing, T.J., 1975: A comparison of map-pattern correlation and principal component eigenvector methods for analyzing climatic anomaly patterns. Preprint Vol., Amer. Meteor. Soc.

Bowie, E.H., 1906: The relation between storm movement and pressure distribution. Mon. Wea. Rev., 34(2), 61-64.

------and R.H. Weightman, 1914: Types of storms of the U.S. and their average movements. Mon. Wea. Rev., 42(supp. 1), 3-13.

Brier, G.W. and R.A. Allen, 1951: Verification of weather forecasts. In T. Malone (ed.), Compendium of Meteorology, Amer. Meteor. Soc., Boston, 841-848.

Bryson, R.A. and T.B. Starr, 1977: Chandler tides in the atmosphere. J. Atmos. Sci., 34, 1975-1986.

CLIMAP Project Members, 1976: The surface of the Ice-Age Earth. Science, 191, 1131-1137.

Colucci, S.J., 1976: Winter cyclone frequencies over the eastern U.S. and adjacent western Atlantic, 1964-1973. Bull. Amer. Meteor. Soc., 57(5), 548-553.

Dickson, R.R. and J. Namias, 1976: North American influences on the circulation and climate of the North Atlantic sector. Mon. Wea. Rev., 104(10), 1255-1265.

Fritts, H., T. Blasing, B. Hayden, and J. Kutzbach, 1971: Multivariate techniques for specifying tree growth and climate relationships and for reconstructing anomalies in paleoclimate. J. Appl. Meteor., 10, 845-864.

Gilman, D., 1957: Empirical orthogonal functions applied to thirty-day forecasting. Sci. Rept. No. 1, MIT, Dept. of Meteor. CFSTI, 120 pp (NTIS AD117249).

Harrison, W., N.A. Pore, and D.R. Tuck, 1965: Predictor equations for beach processes and responses. J. Geophys. Res., 70(24), 6103-6109.

Hayden, B.P., 1975: Storm wave climates at Cape Hatteras, N.C., recent secular variations. Science, 190, 981-983.

------1980a: Secular variation in Atlantic coast extratropical cyclones. Mon. Wea. Rev., in press.

------1980b: Cyclone occurrence mapping--equal area or raw frequencies. Mon. Wea. Rev., in press.

Heidke, P., 1926: Berechnung des erfolges und der gute der windstarkevorhersagen im sturmwarnungsdienst. Geogr. Ann., 8, 310-349.

Hosler, C.L., and L.A. Gamage, 1956: Cyclone frequencies in the U.S. for the period 1905-1954. Mon. Wea. Rev., 84(11), 388-390.

Huntington, E., 1914a: The shifting of climatic zones. In E. Huntington, The Climatic Factor as Illustrated in Arid America. Carnegie Inst. of Washington, Pub. No. 192, 189-192.

------1914b: The solar hypothesis of climatic changes. Bull. Geol. Soc. of Am., 25, 477-590.

Hurley, J.C., 1954: Statistics on the movement and deepening of cyclones in the Middle West. Mon. Wea. Rev., 82(5), 116-122.

James, R.W., 1952: The latitude dependence on intensity in cyclones and anticyclones. J. Meteor., 9, 243-251.

Klein, W.H., 1948: Winter precipitation as related to the 700-Mb circulation. Bull. Amer. Meteor. Soc., 29(9), 439-442.

------1957: Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. U.S. Weather Bur. Res. Paper, 40, 60p.

------1958: The frequency of cyclones and anticyclones in relation to the mean circulation. J. Meteor., 15, 98-102.

Kullmer, C.J. 1914: The shift of the storm track. In E. Huntington, The Climatic Factor as Illustrated in Arid America. Carnegie Inst. of Washington, Pub. No. 192, 193-210.

Kullmer, C.J., 1933: The latitude shift of the storm track in the 11-year solar period. Smiths. Misc. Coll., 89(2), 1-34.

------1943: A remarkable reversal in the distribution of storm frequency in the U.S. in double hale solar cycles, of interest in long-range forecasting. Smiths. Misc. Coll., 103(10), 1-20.

Kutzbach, J., 1967: Empirical eigenvectors of sea-level pressure, surface temperature and precipitation complexes over North America. J. Appl. Meteor., 6, 791-802.

Lorenz, E., 1956: Empirical orthogonal functions and statistical weather prediction. Sci. Rept. No. 1, MIT, Dept. of Meteor. CFSTI, 49 pp (NTIS AD110268).

Mather, J.R., H. Adams and G. Yoshioka, 1964: Coastal storms of the eastern U.S. J. Appl. Meteor., 3, 693-706.

------R.T. Field and G. Yoshioka, 1967: Storm damage hazards along the east coast of the U.S. J. Appl. Meteor., 6, 20-30.

Miller, J.E., 1946: Cyclogenesis in the Atlantic coastal region of the U.S. J. Meteor., 3, 31-44.

------and H.T. Mantis, 1947: Extratropical cyclogenesis in the Pacific coastal region of Asia. J. Meteor., 4, 29-34.

Namias, J., 1960: Synoptic and planetary scale phenomena leading to the formation and recurrence of precipitation. Mono., Am. Geophys. Union, 5, 32-44 (387-399).

------1974: Longevity of coupled air/sea continent system. Mon. Wea. Rev., 102(9), 638-648.

Namias, J., G. Dunn and R. H. Simpson, 1955: A survey of a hurricane problem. Trans., N.Y. Acad. Sci., February, Series 11(17), 346-352.

Petterssen, S., 1941: Cyclogenesis over southeastern U.S. and the Atlantic coast. Bull. Amer. Meteor. Soc., 22, 269-280.

Reitan, C.H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951-1970. Mon. Wea. Rev., 102(11), 861-868.

------1979: Trends in the frequencies of cyclone activity over North America. Mon. Wea. Rev., 107, 1684-1688.

Resio, D.T. and B.P. Hayden, 1975: Recent secular variations in mid-Atlantic winter extratropical storm climate. J. Appl. Meteor., 14(7), 1223-1234.

Saucier, W.J., 1949: Texas-West Gulf cyclones. Mon. Wea. Rev., 77(8), 219-231.

Serfling, R.J., 1975: The poisson distribution for the frequency of rare levels of persistent meteorological elements. Preprints, Fourth Conf. on Prob. and Stats. in Atmos. Sciences, 135-138.

Torranin, P., 1972: Applicability of canonical correlation in hydrology. Colorado State Univ., Hydrology Paper No. 58, Fort Collins, Col., 30 p.

Vernon, E.M., 1953: A new concept of skill score for rating quantitative forecasts. Mon. Wea. Rev., 81(10), 326-329.

Vincent, L., R. Dolan, B. Hayden and D. Resio, 1976: Systematic variations in barrier island topography. J. Geol., 84, 583-594.

Walker, G.T. and E.W. Bliss, 1932: World Weather V. Mem., Roy. Meteor. Soc., 4(36), 53-84.

Webb, T. and R.A. Bryson, 1972: Late and postglacial climatic change in the northern Midwest, U.S.A. Quat. Res., 2, 70-115.

Weightman, R.H., 1945: Average monthly tracks by types of lows in the U.S. U.S. Weather Bur. Res. Paper, Washington, D.C.

Zishka, K.M. and P.J. Smith, 1980: The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950-1977. Mon. Wea. Rev., 108(4), 387-401.

FIGURE CAPTIONS

Figure 1: Chart of the study area. The rectangular inset is 2.5° latitude by 5.0° longitude. There are 74 such rectangular grid cells in the study area. The arrow represents a storm track passing through the grid cell shown.

Figure 2: Mean Winter (A) and Summer (B) cyclone frequency for the years 1885-1979. Winter includes the months of October thru March and summer consists of April through September. Units are cyclones per 2.5° latitude-5° longitude grid cell.

Figure 3: Standard deviations of mean Winter (A) and Summer (B) cyclone frequency for the years 1885-1979.

Figure 4: Percent variance explained versus eigenvector number for the first 21 eigenvectors of Winter and Summer cyclone frequency matrices and for matrices of the same dimensions constructed by randomizing the original winter and summer matrices.

Figure 5: The first eigenvectors of Winter (A) and Summer (B) cyclone frequencies.

Figure 6: The second eigenvectors of Winter (A) and Summer (B) cyclone frequencies.

Figure 7: The third eigenvectors of Winter (A) and Summer (B) cyclone frequencies.

Figure 16: Histograms of frequencies of local skill scores in 5% class intervals for the Winter (A) and Summer (B). Forecasts shown in Figure 14.

Figure 17: Forecast for the winter of 1979-1980 and verification. A shows the predicted cyclone frequency pattern in cyclones per grid cell. Dashed lines indicate the predicted mean storm track as evidenced by local maxima in the data field. B shows the actual occurrences of cyclones for the winter and the mean storm track. C shows the difference pattern between the predicted and the long-term mean and D the difference between the actual cyclone occurrence and the mean. E shows the difference between the predicted and the actual. Solid circles indicate correct forecast; open circles are failures.

TABLE 1

Eigenvector	Percent Variance Explained Winter	Summer
1	24.5	20.8
2	17.0	14.1
3	6.1	7.6
4.	4.8	5.2

TABLE 2

	Pearson Correlation Coefficients
Summer versus the Following Winter	
E_1	.74*
E_2	.52*
E_3	.10
E_4	-.46*
Winter versus the Following Summer	
E_1	.74*
E_2	.51*
E_3	.10
E_4	-.46*

* = Significant at the .00001 level

TABLE 3

SUMMARY OF ESTIMATES OF GLOBAL FORECAST SKILL

For the University of Virginia Climate Prediction Model

	Winter 1885/86-1978/79	Summer 1886-1979
PERCENT SKILL SCORE	66%	66%
HEIDKE SKILL SCORE	0.34	0.32
DEVIATION SKILL SCORE	0.08	0.10
QUADRATIC SKILL DEVIATION	0.14	0.15
AVERAGE CYCLONES PER GRID CELL	5.9	4.0
AVERAGE STANDARD DEVIATION OF CYCLONES PER GRID CELL	2.9	2.1
AVERAGE ABSOLUTE ERROR FOR FORECAST	2.30	1.91
AVERAGE ABSOLUTE ERROR FOR MEAN AS FORECAST	2.57	2.37
ROOT MEAN SQUARE ERROR FOR FORECAST	3.07	2.55
FOOT MEAN SQUARE ERROR FOR MEAN AS FORECAST	3.39	2.86

TABLE 4

Summary of correlations between eigenvector weighting departures from fitted third order polynomials (P D) global skill scores (S) in the following season

	PEARSON Correlation	Regression Slope*	Significance Level
Winter S vs Summer PD			
E_1	-.14	-1.30	.095
E_2	+.07	+ .48	.246
E_3	-.05	- .49	.318
E_4	+.03	+ .40	.376
Summer S vs Winter PD			
E_1	-.22	-1.82	.015
E_2	-.04	- .28	.343
E_3	-.04	- .40	.340
E_4	+.19	+2.31	.031

* the units on the regression slope are percentage points of global skill per unit eigenvector weighting

TABLE 5

GLOBAL SKILL SCORES FOR THE UNIVERSITY OF VIRGINIA CLIMATE PREDICTION MODEL RELATIVE TO THE LONG-TERM (1885-1979) MEAN, CHANCE, PERSISTENCE AND THE PREVIOUS SEASON (prorated) AS FORECASTS. WINTER SKILL VALUES ARE GIVEN AND ARE FOLLOWED BY SUMMER SKILL VALUES IN PARENTHESES.

	MEAN	CHANCE	PERSISTENCE	PREVIOUS SEASON
PERCENT SKILL SCORE	66 (66)	73 (71)	56 (57)	75 (66)
HEIDKE SKILL SCORE	.34 (.32)	.45 (.44)	.12 (.13)	.49 (.31)
DEVIATION SKILL SCORE	.08 (.10)	.27 (.28)	-.05(-.07)	.27 (.10)
QUADRATIC SKILL SCORE	.14 (.15)	.45 (.47)	-.13(-.17)	.45 (.18)
AVERAGE ABSOLUTE ERROR FOR MODEL FORECAST	2.30(1.19)	2.30(1.91)	2.30(1.91)	2.30(1.91)
AVERAGE ABSOLUTE ERROR FOR BASE* AS A FORECAST	2.57(2.37)	3.13(2.66)	2.19(1.81)	3.18(2.11)
ROOT MEAN SQUARE ERROR FOR MODEL FORECAST	3.07(2.55)	3.07(2.55)	3.07(2.55)	3.07(2.55)
FOOT MEAN SQUARE ERROR FOR BASE* AS A FORECAST	3.39(2.86)	4.20(3.65)	2.90(2.41)	4.30(2.88)

*the four bases are the mean, chance, persistence and the previous season.

Fig. 1

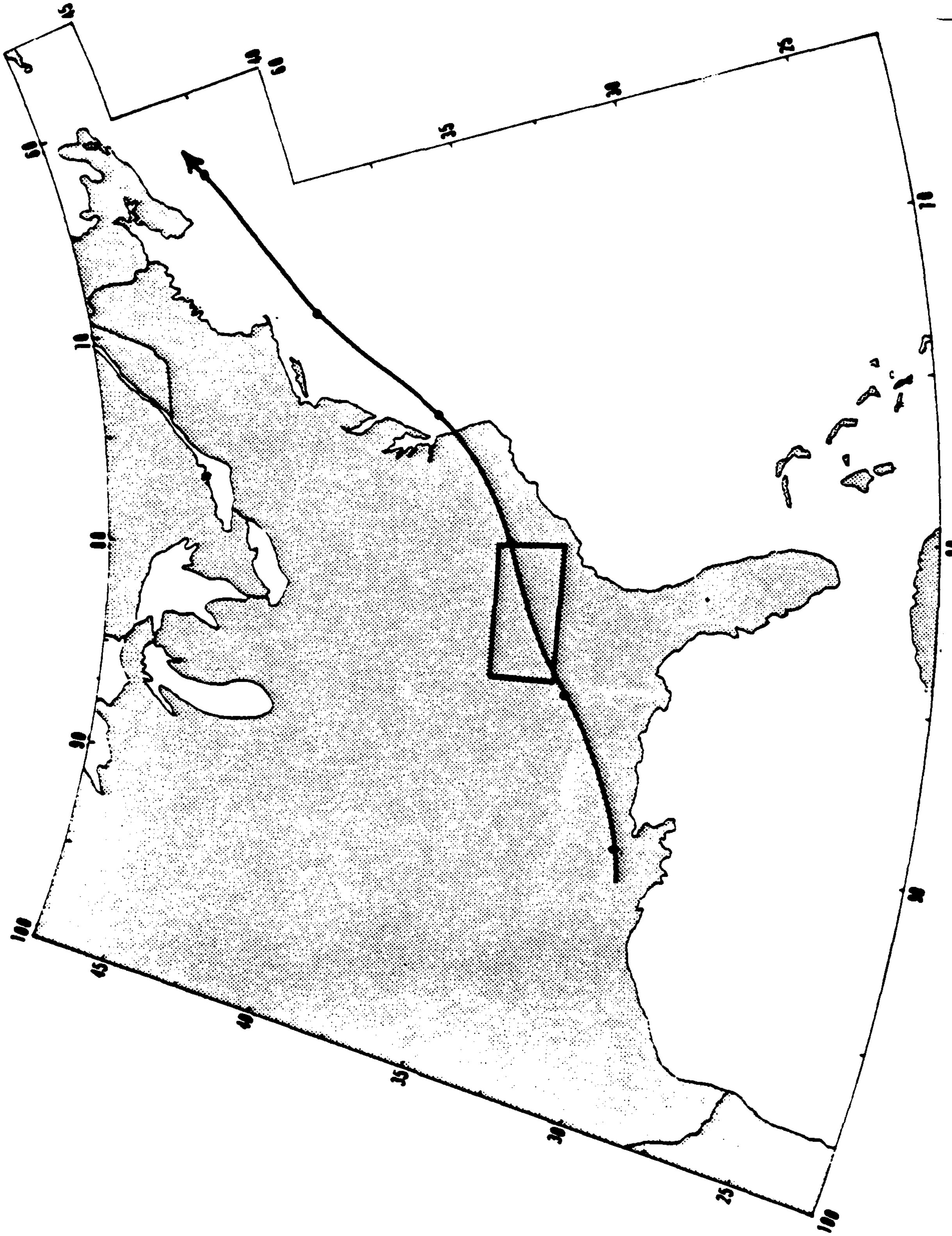


Fig. 2A

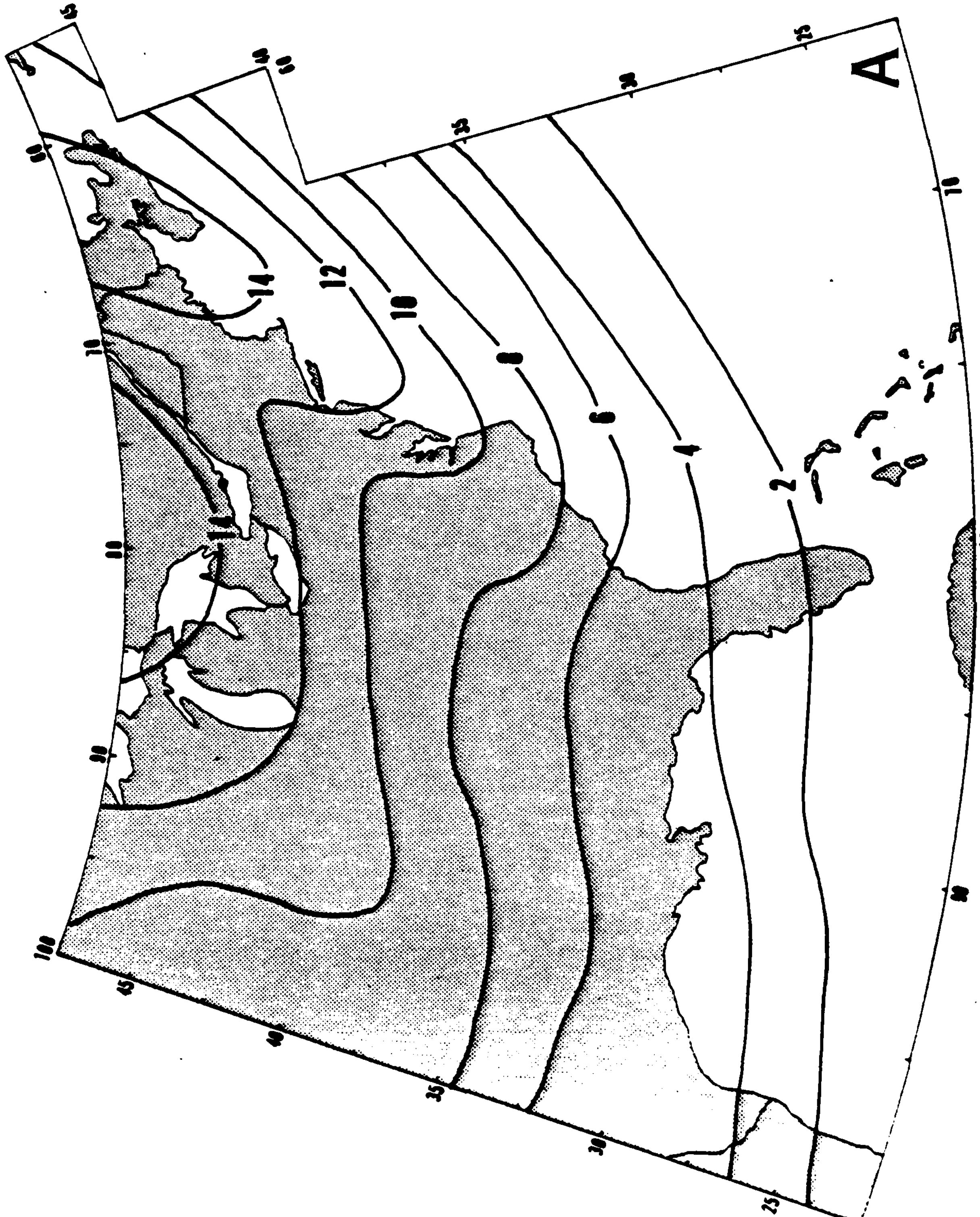


Fig. 28

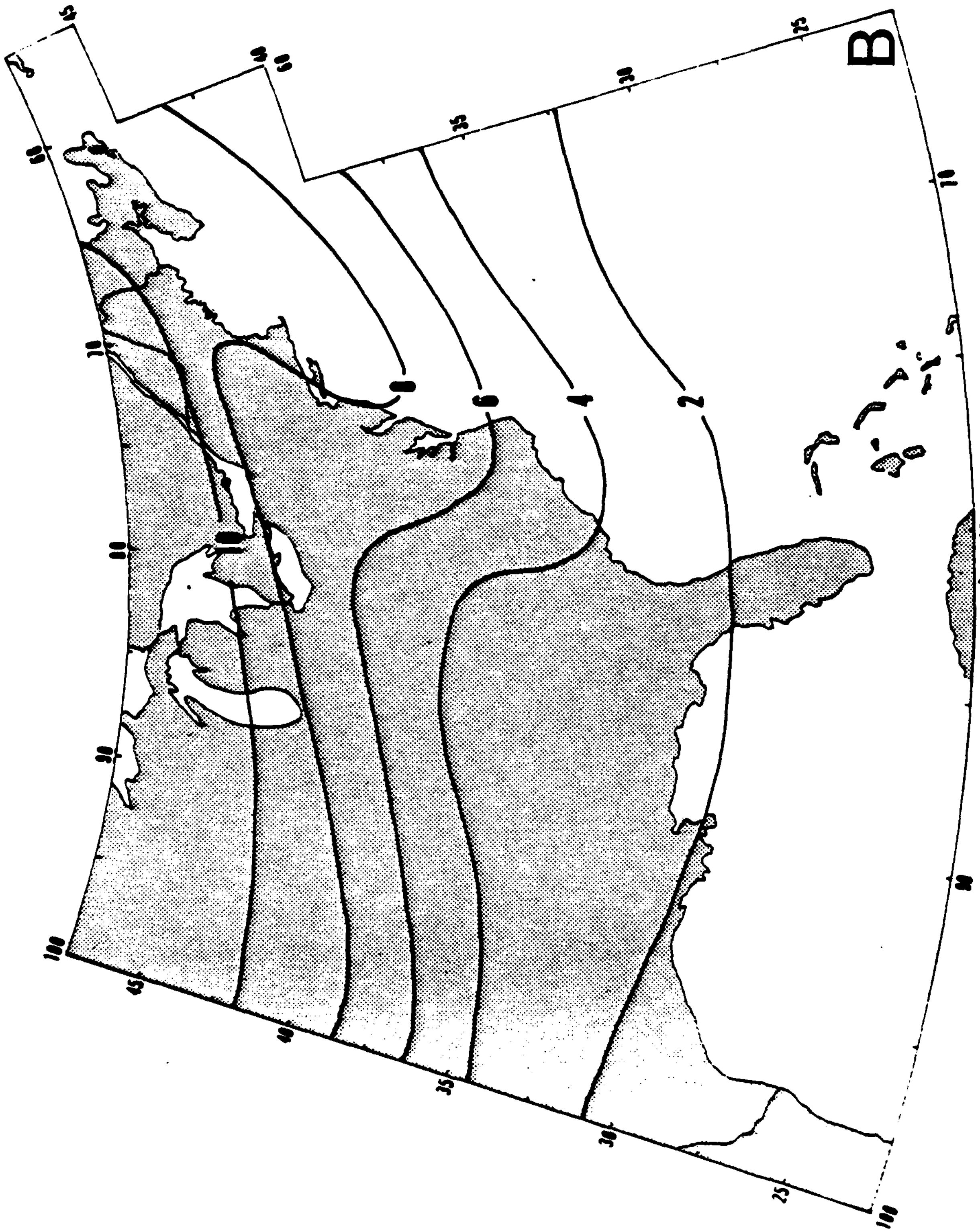
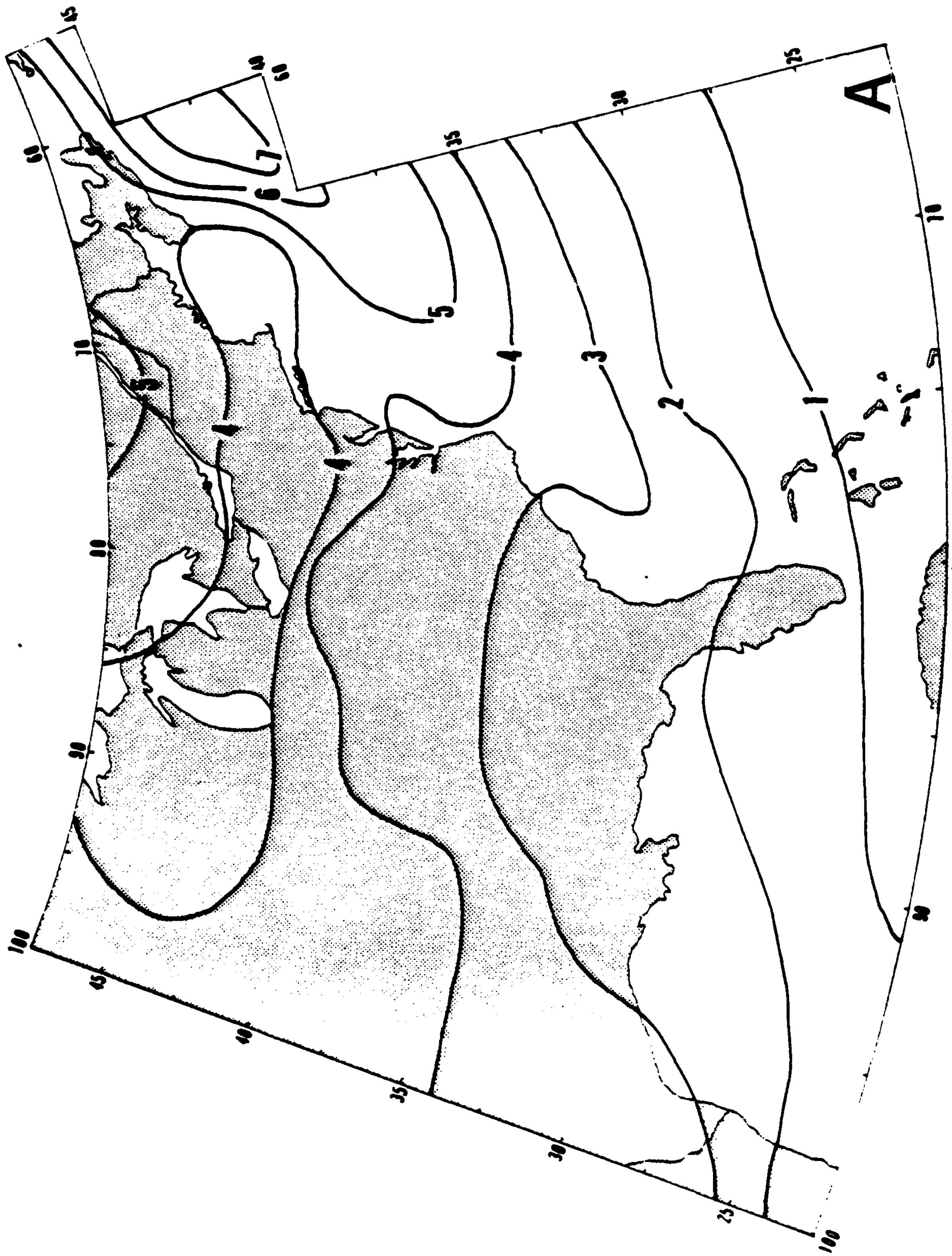


Fig. 3



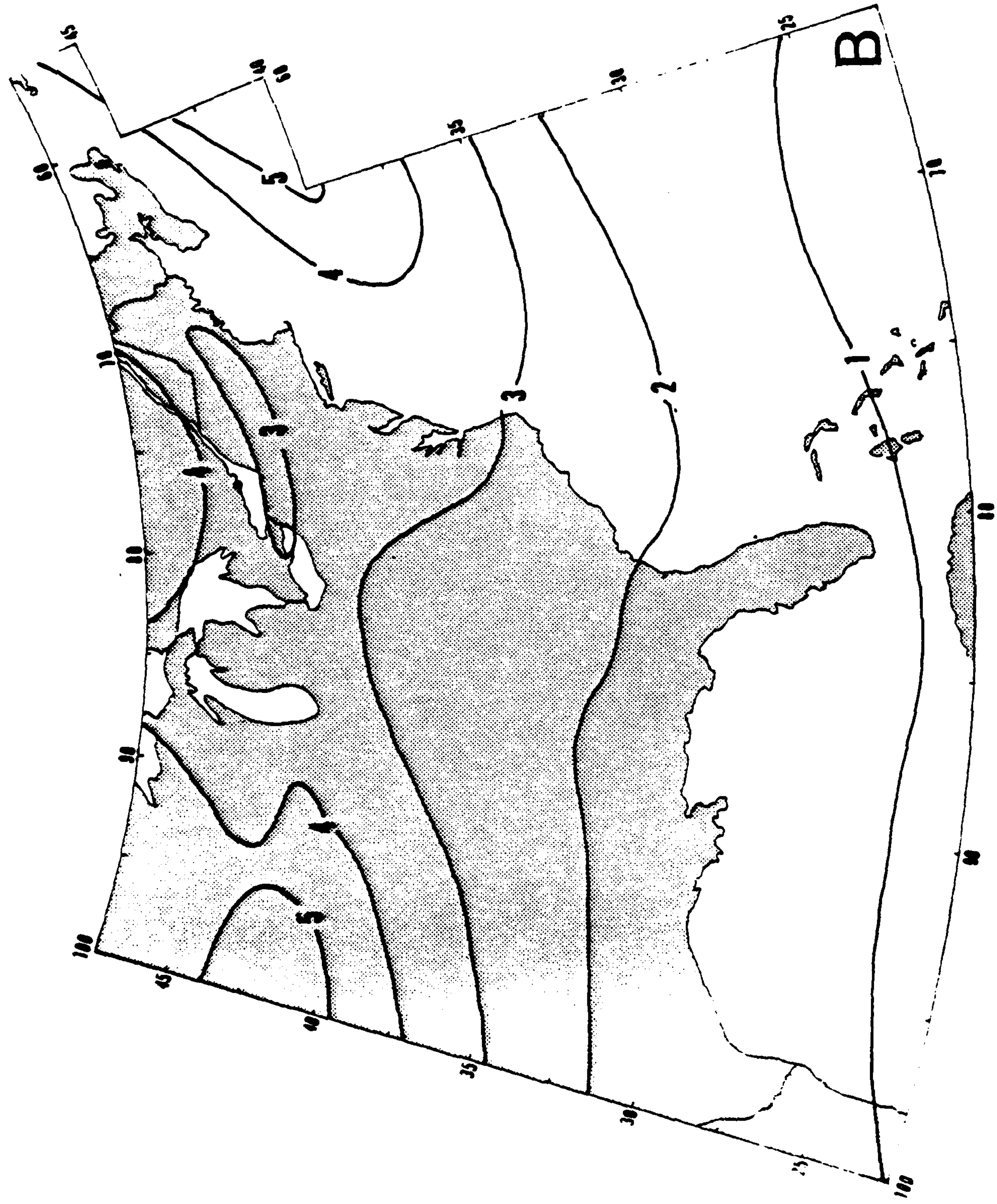
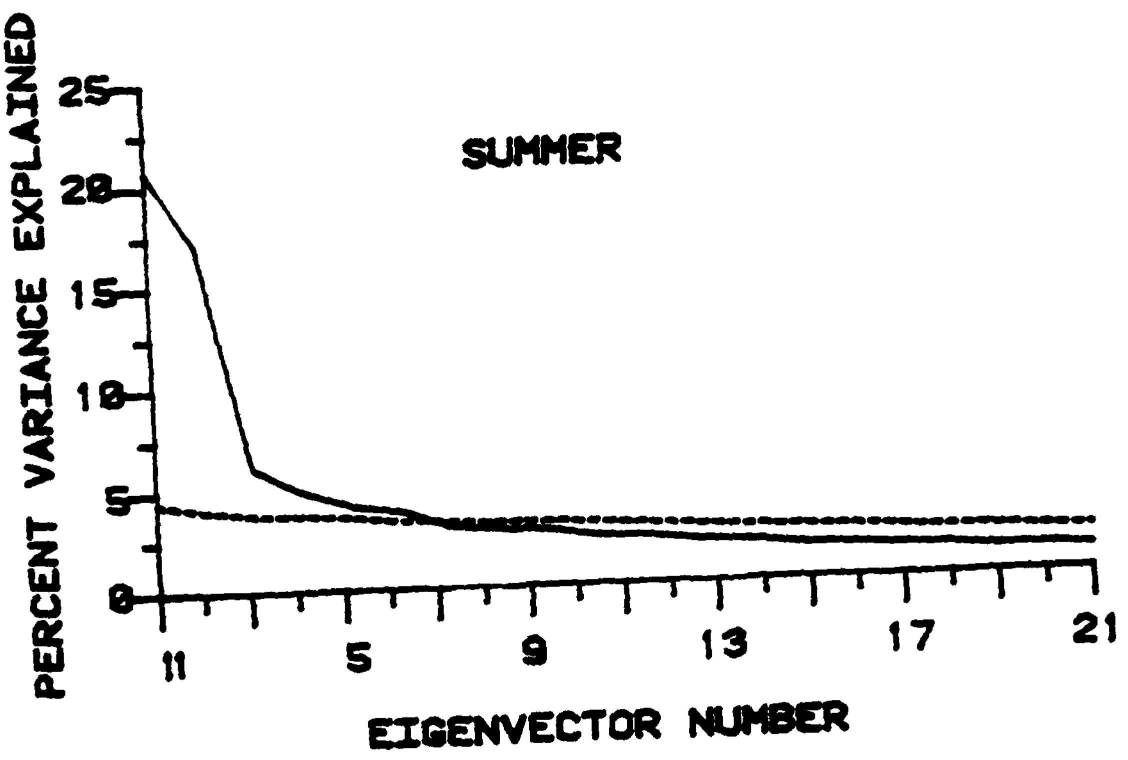
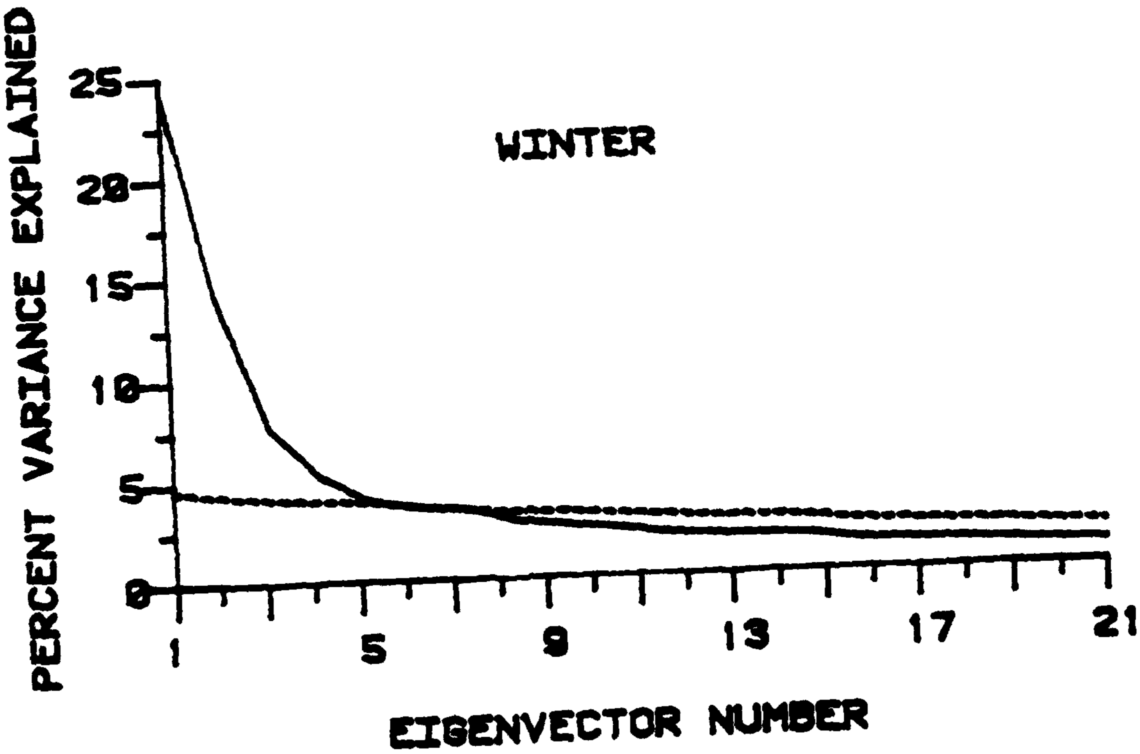


Fig. 3B

Fig. 4



SUMMER
PERCENT VARIANCE EXPLAINED
25
20
15
10
5
0
1
5
9
13
17
21
EIGENVECTOR NUMBER



WINTER
PERCENT VARIANCE EXPLAINED
25
20
15
10
5
0
1
5
9
13
17
21
EIGENVECTOR NUMBER

Fig. 5A

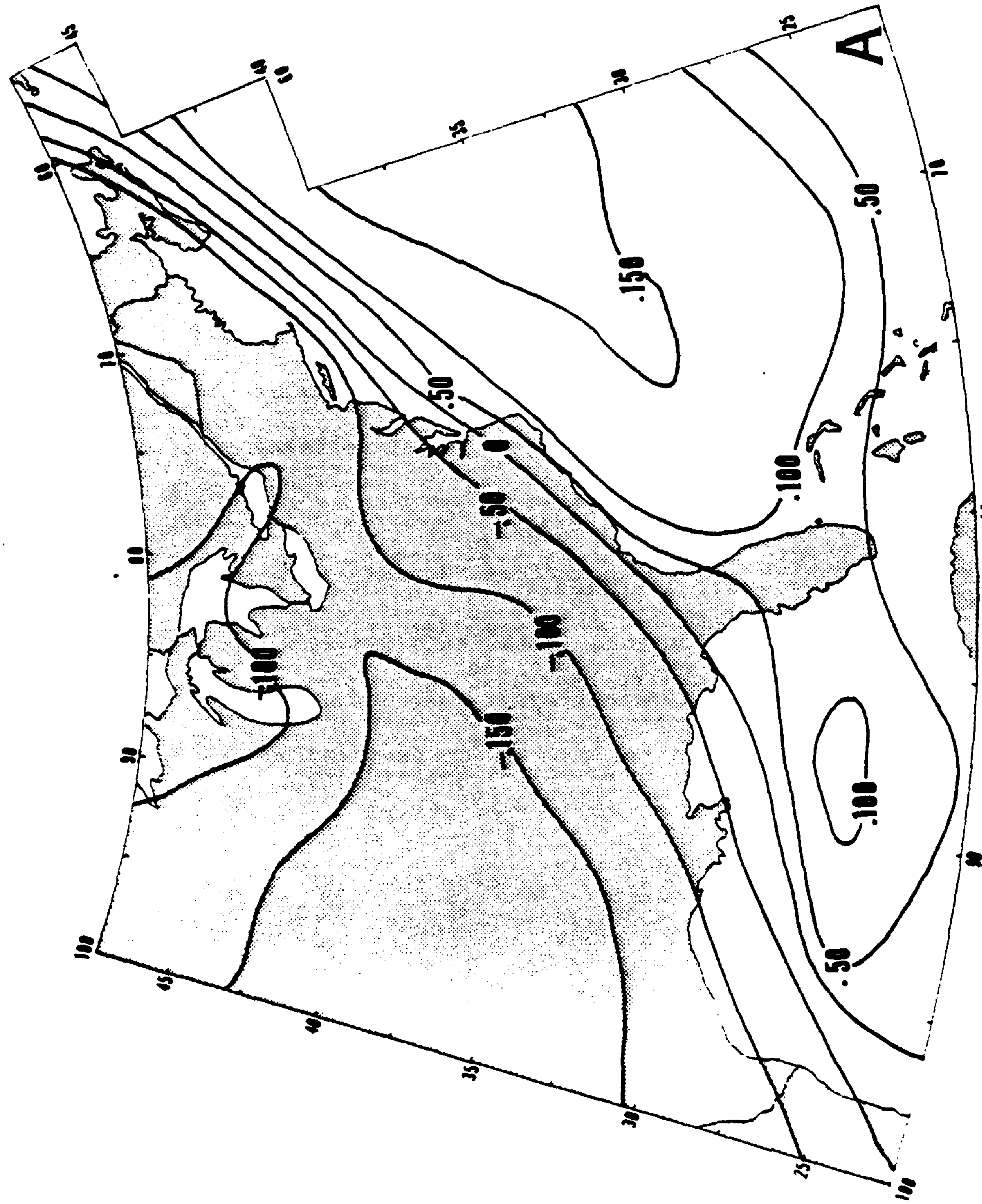


Fig. 53

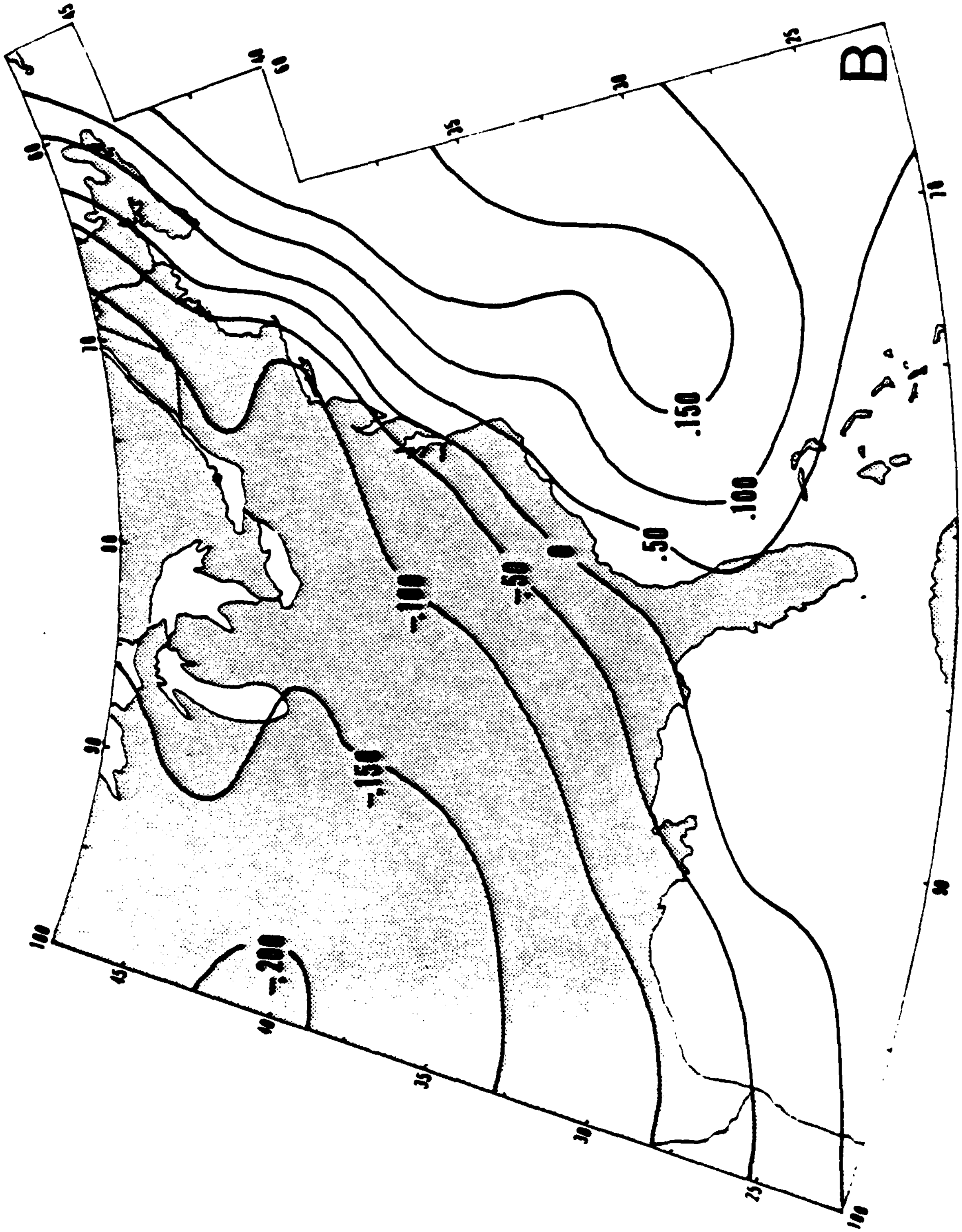


Fig. 6A

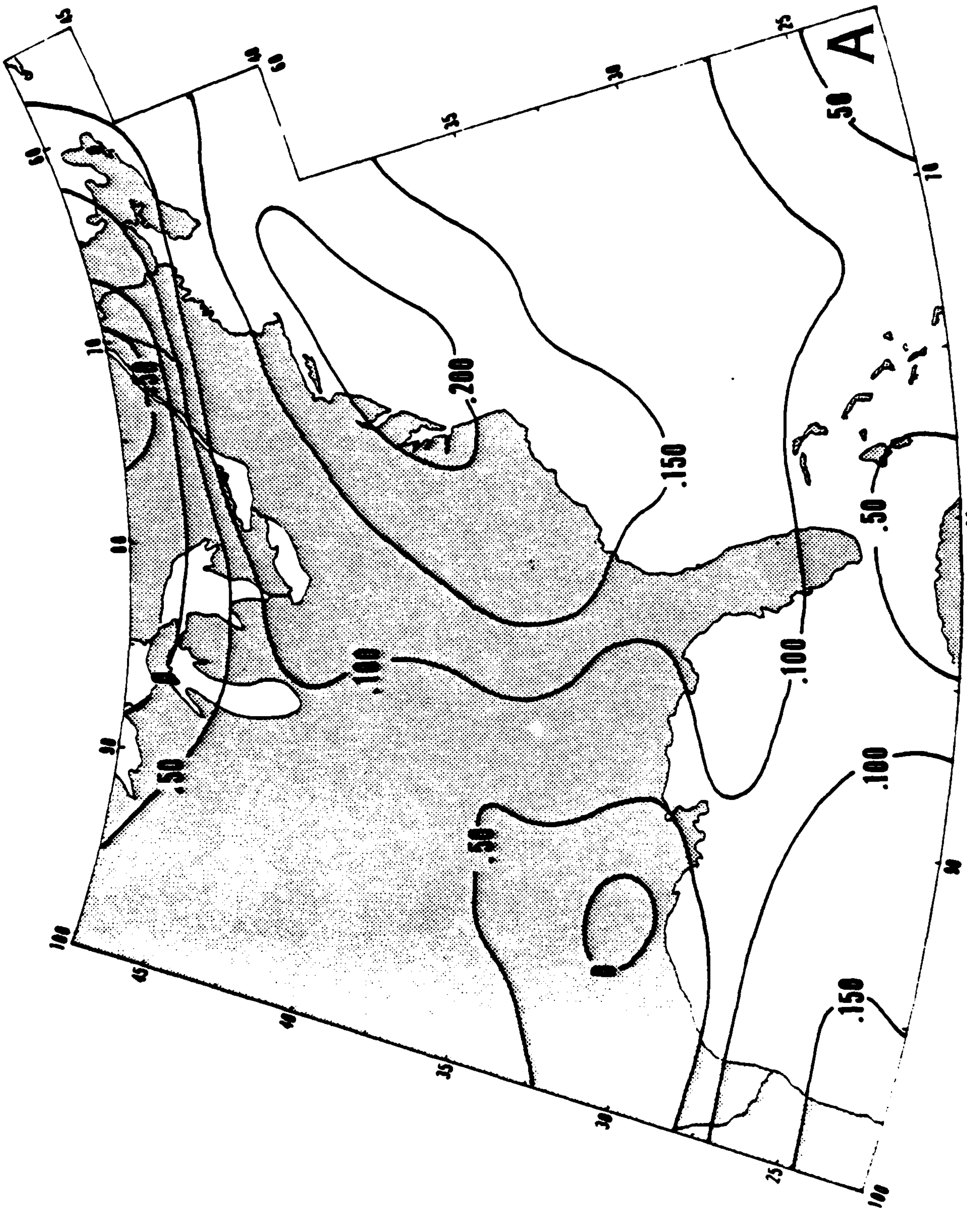


Fig. 6B

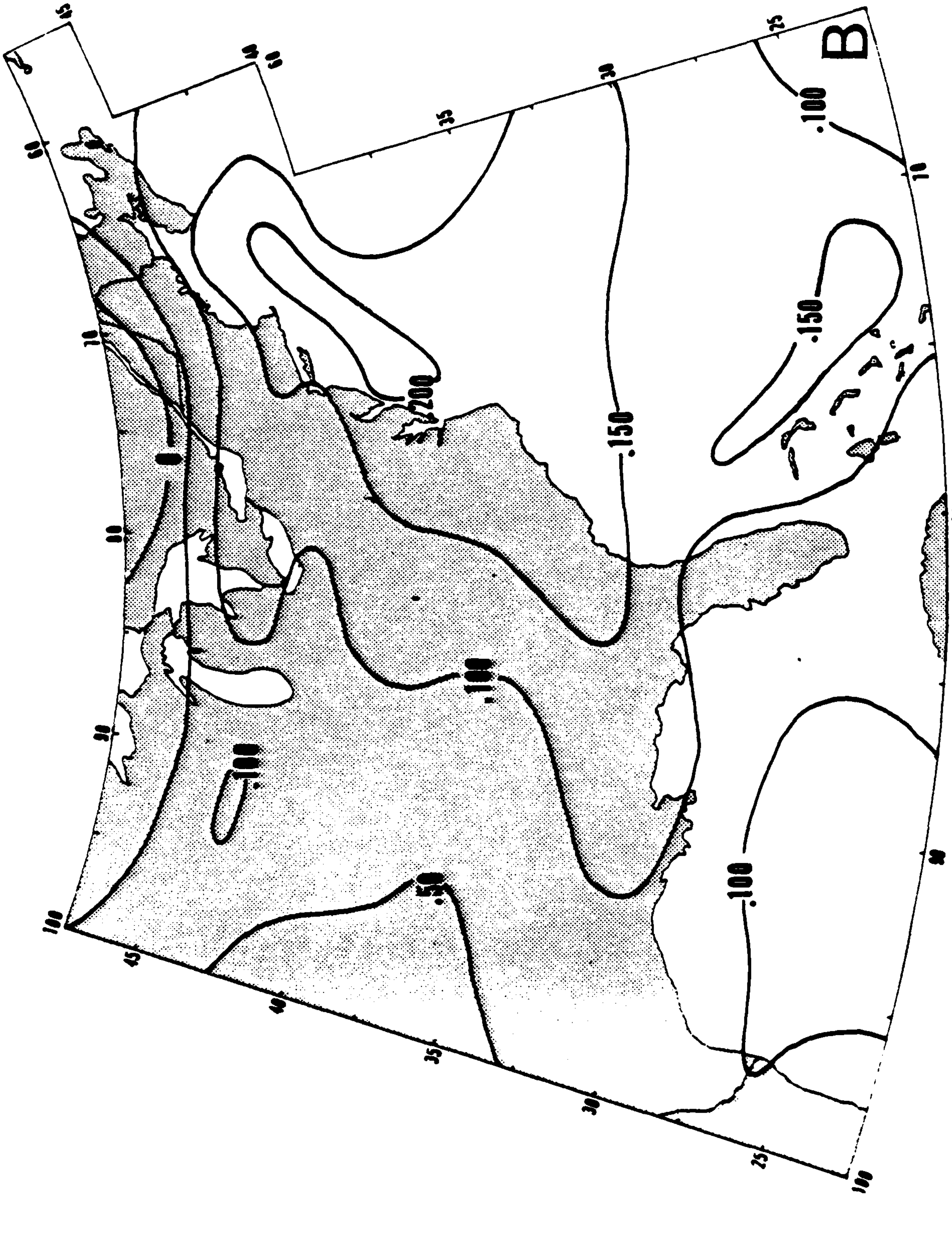


Fig. 7A

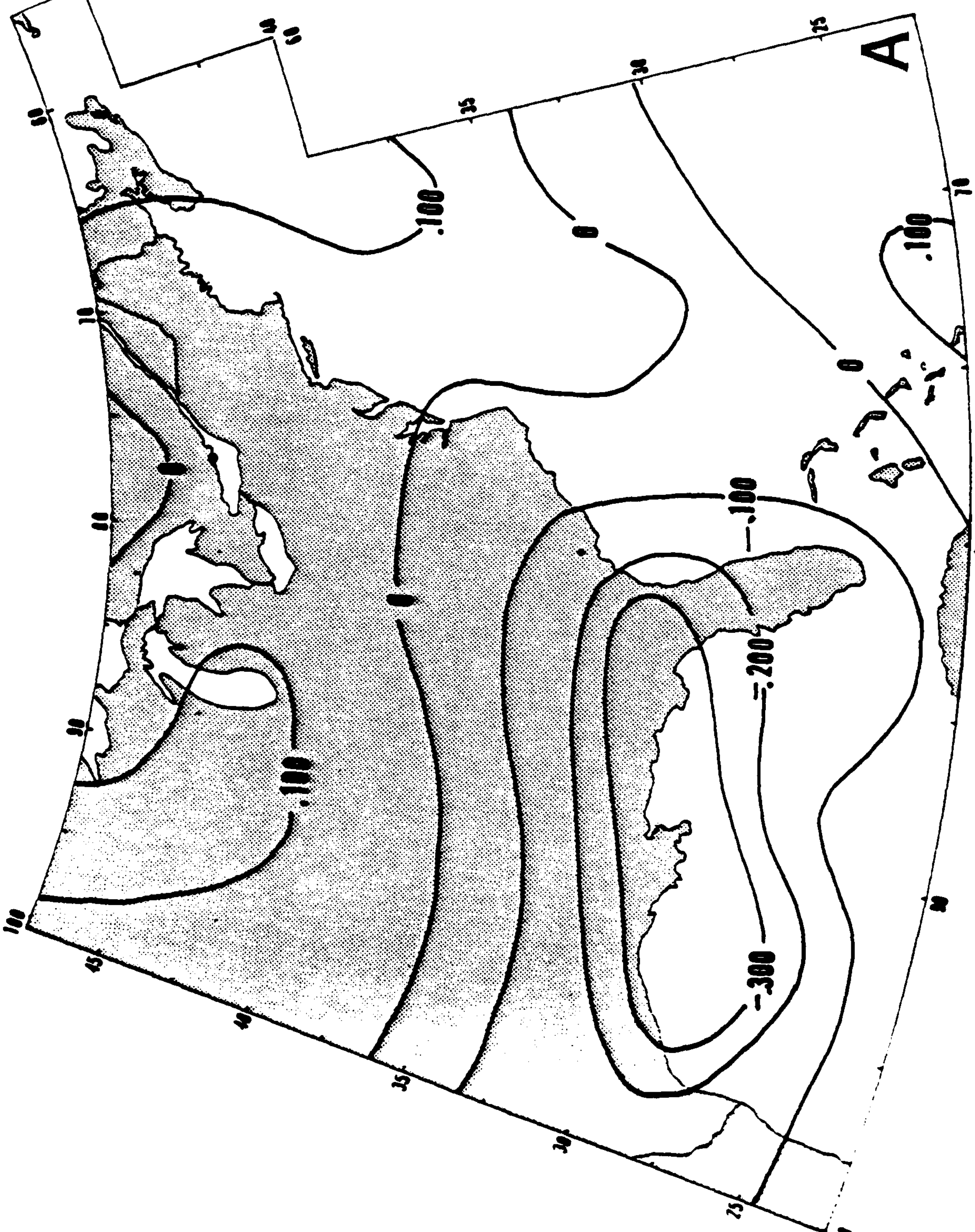


Fig. 7B

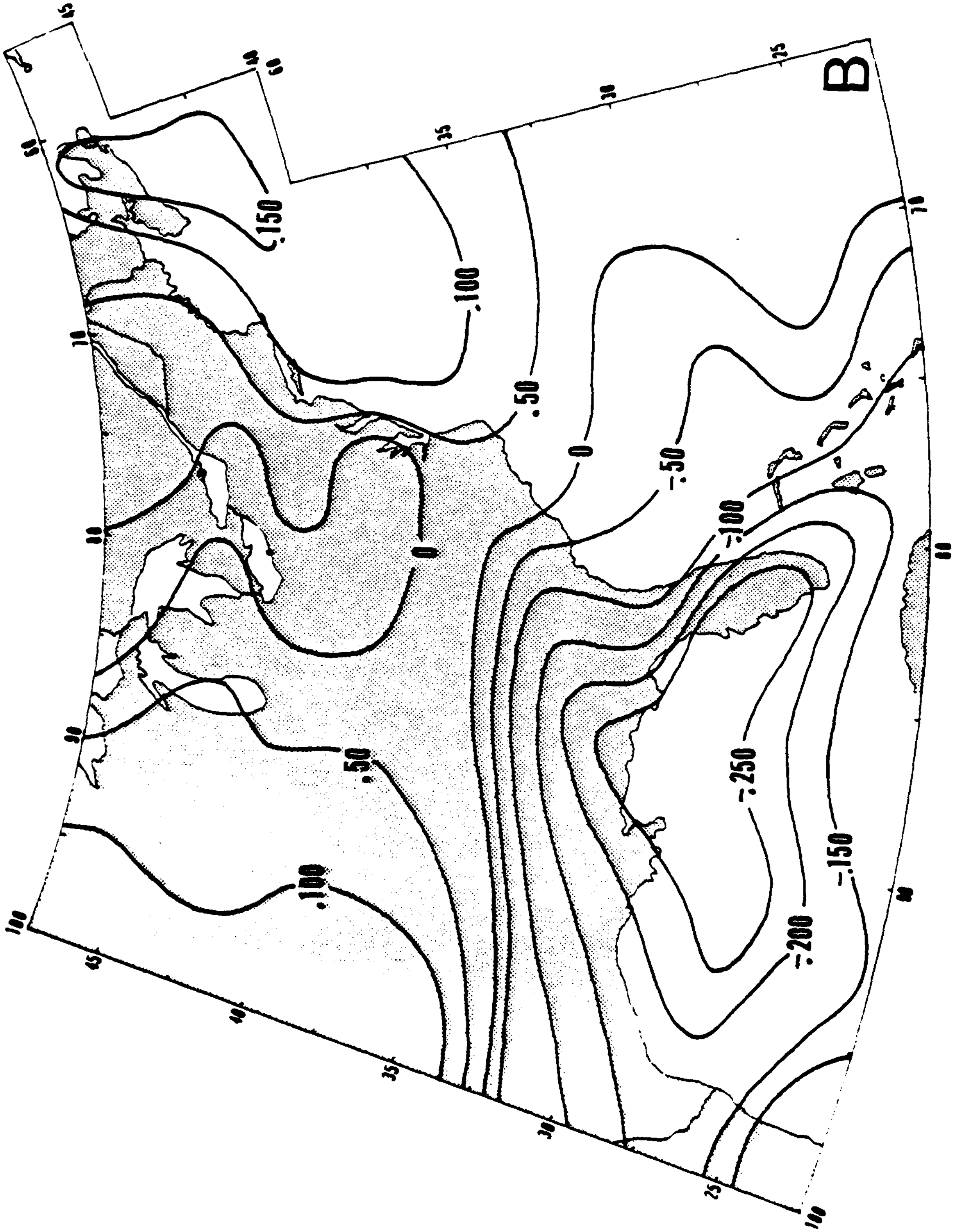


Fig. 8A

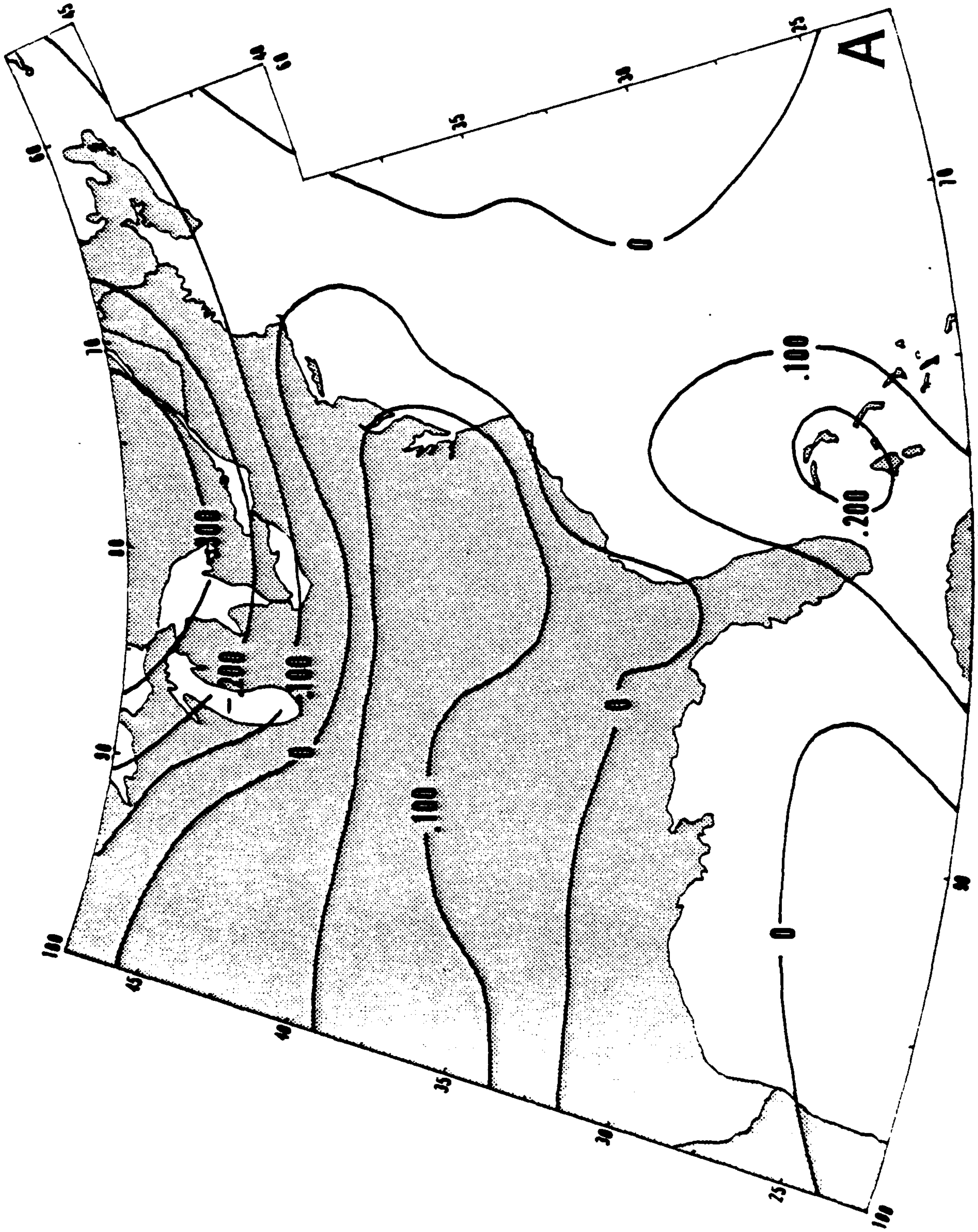
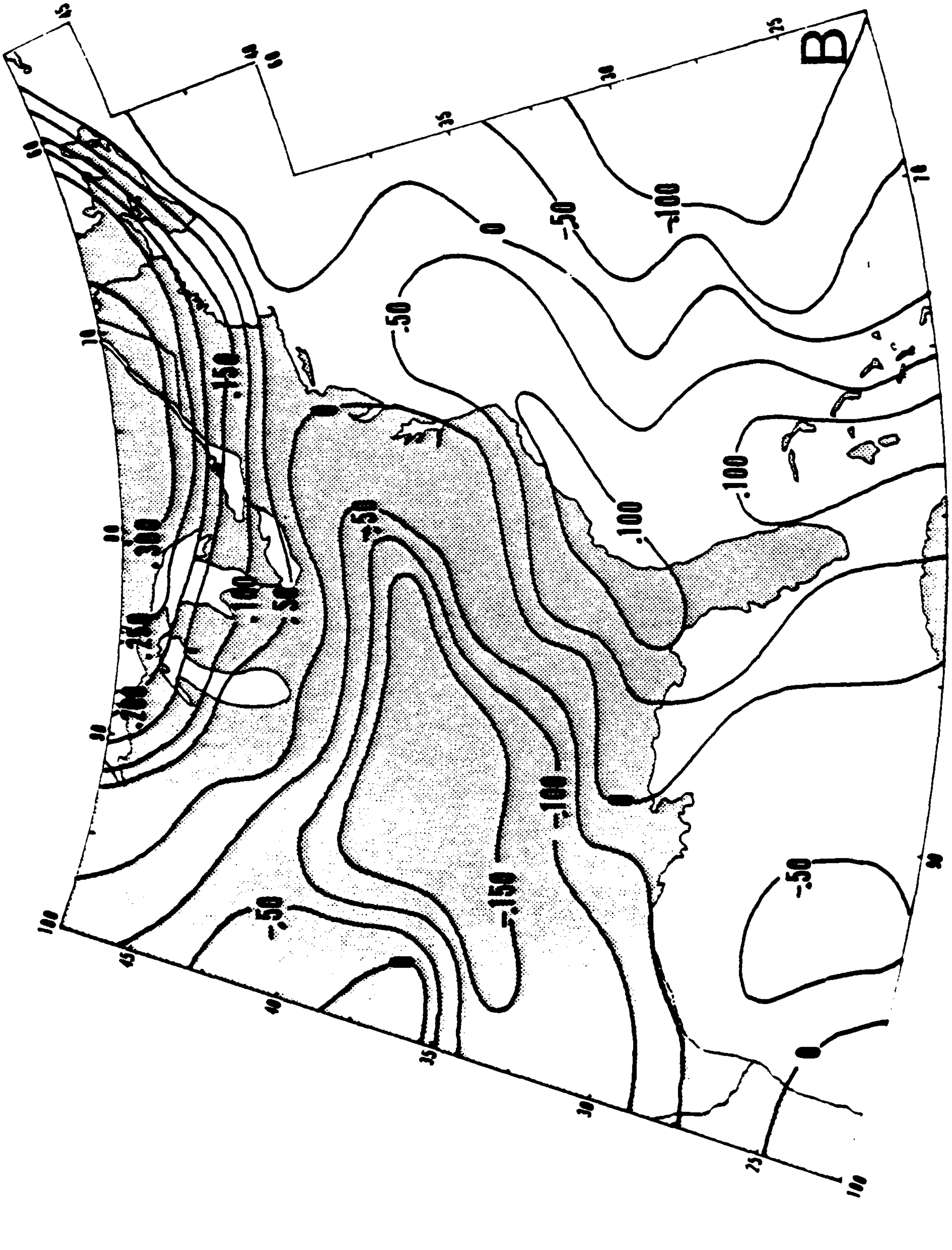


Fig. 8B



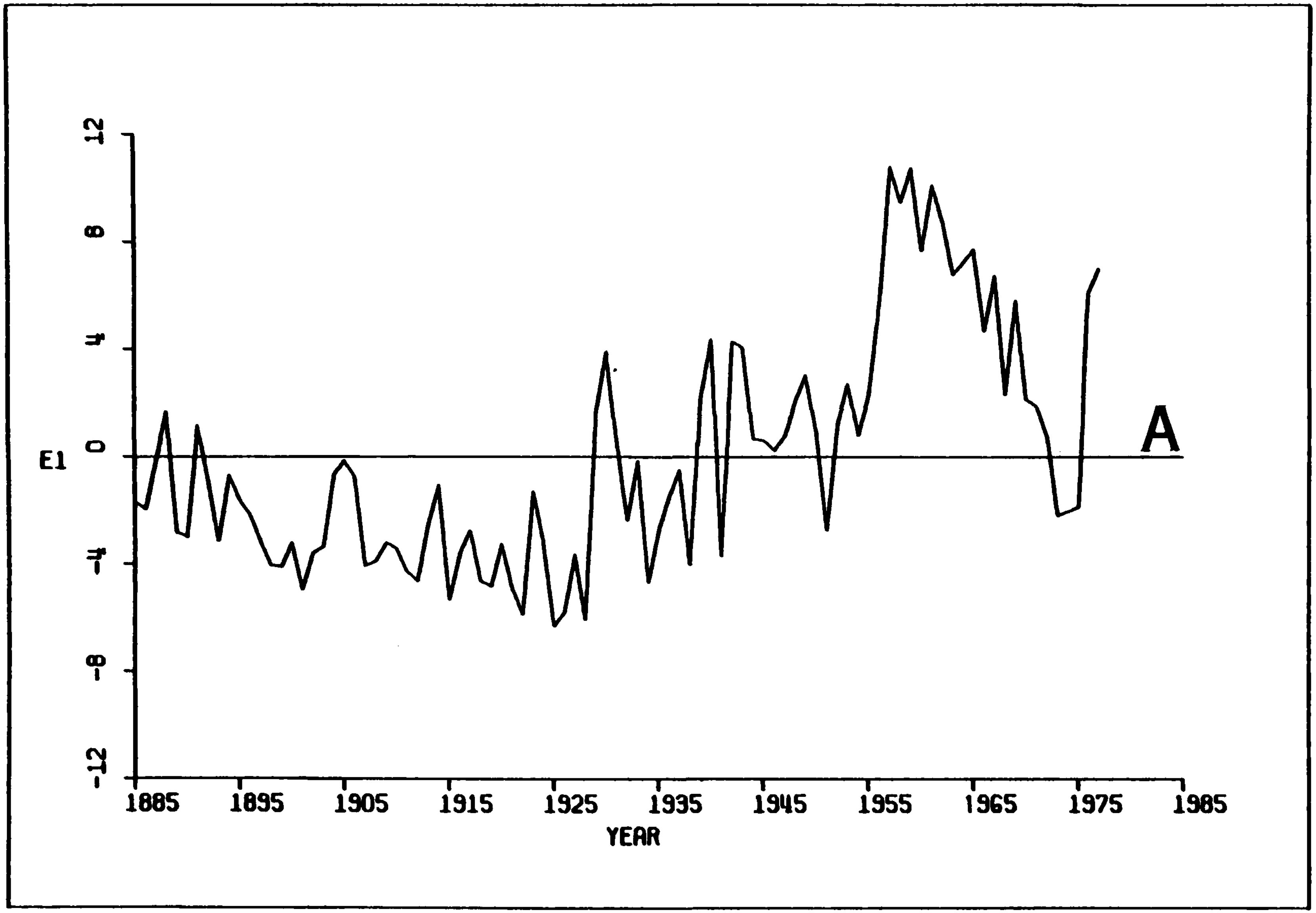

A
E1
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9A-

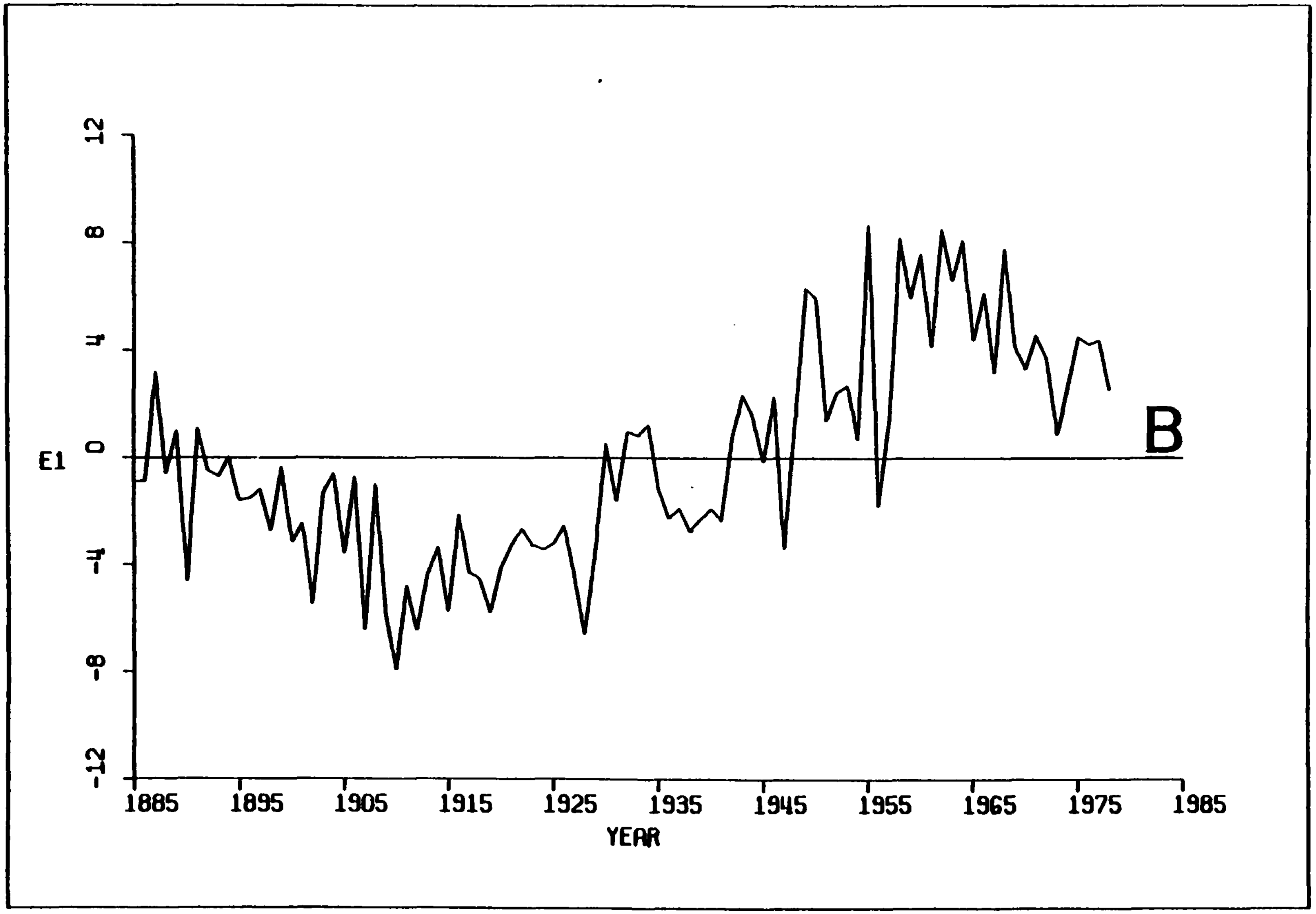

B
E1
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9B-

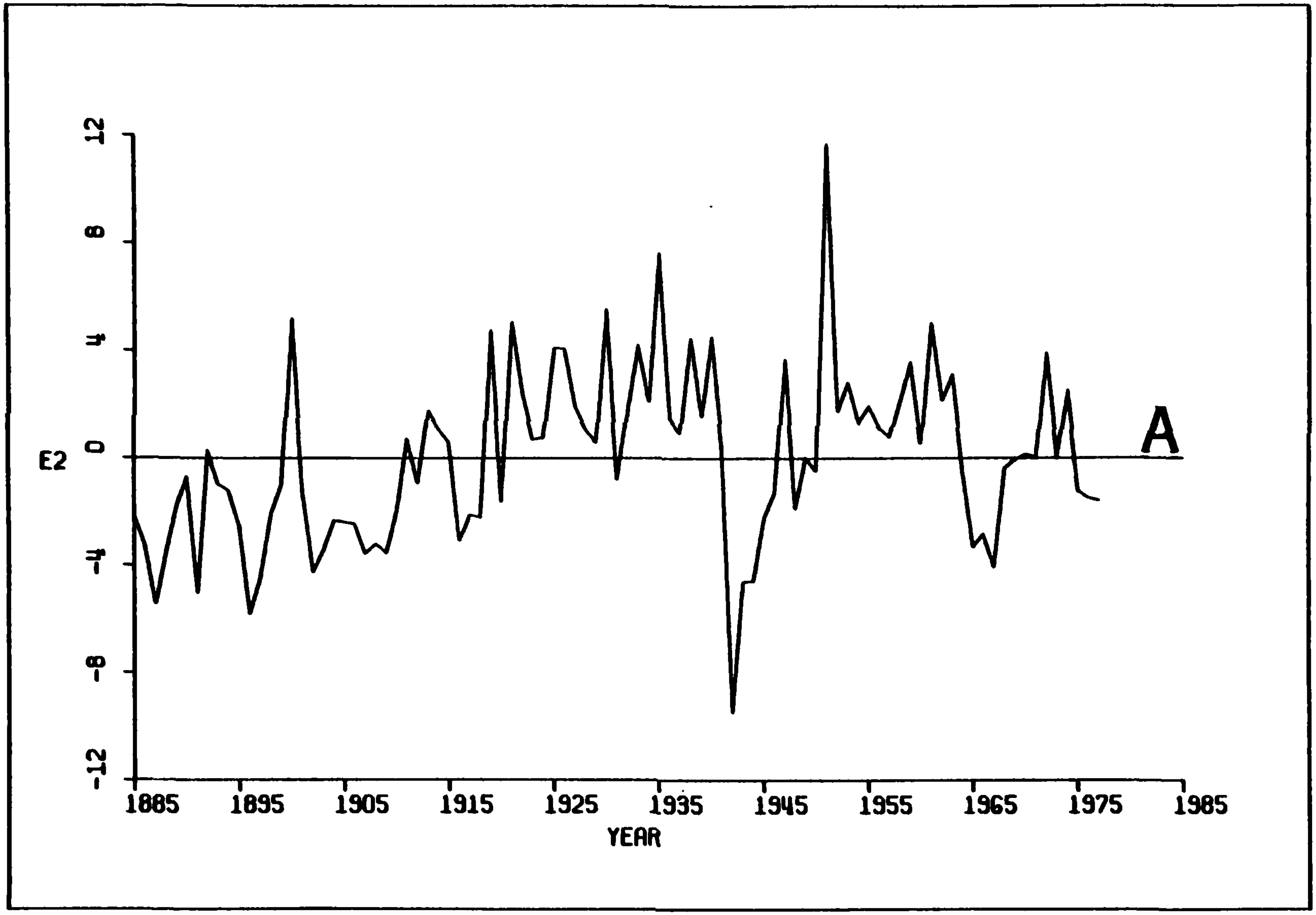

A
E2
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9A-i

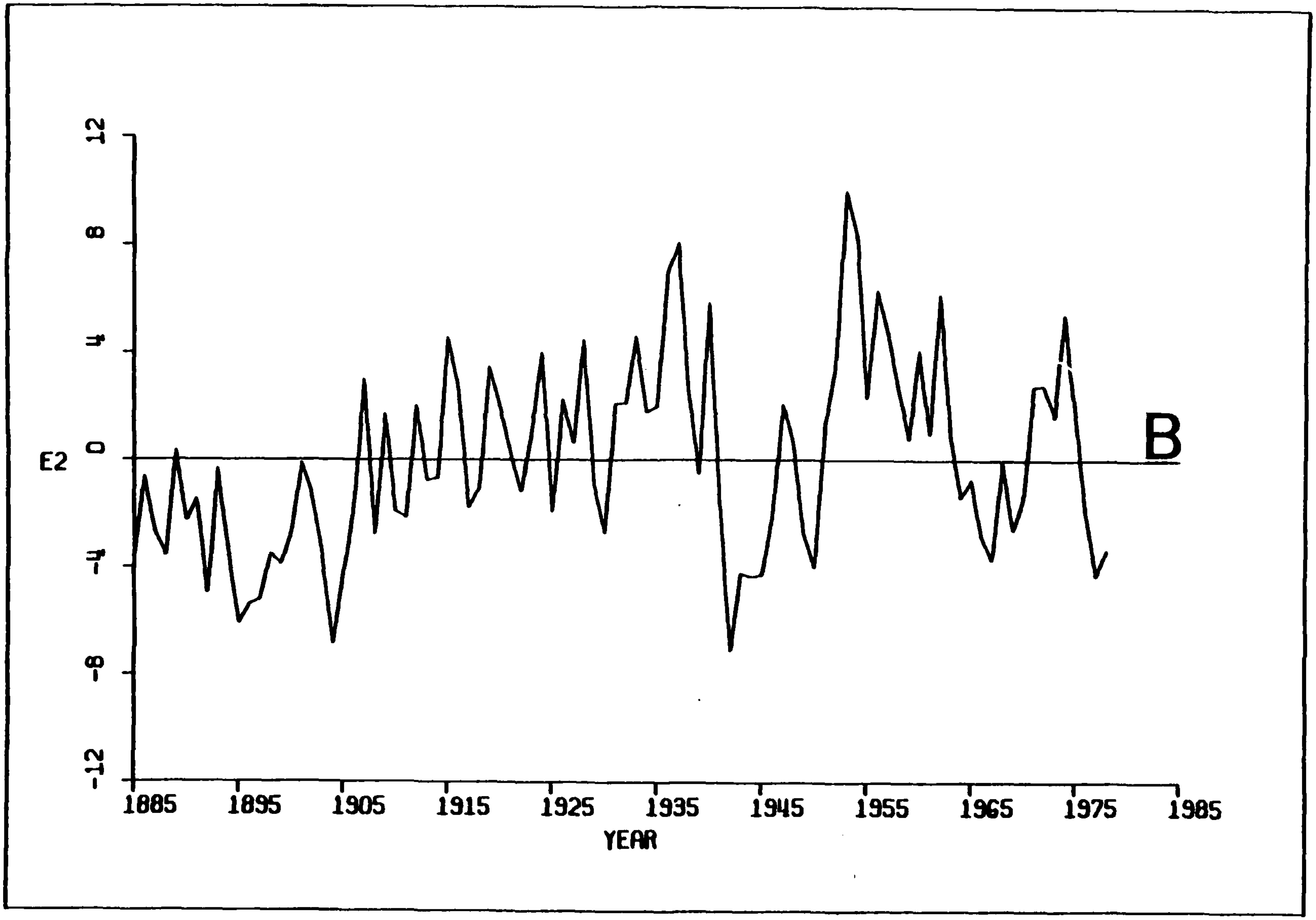

B
E2
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9B

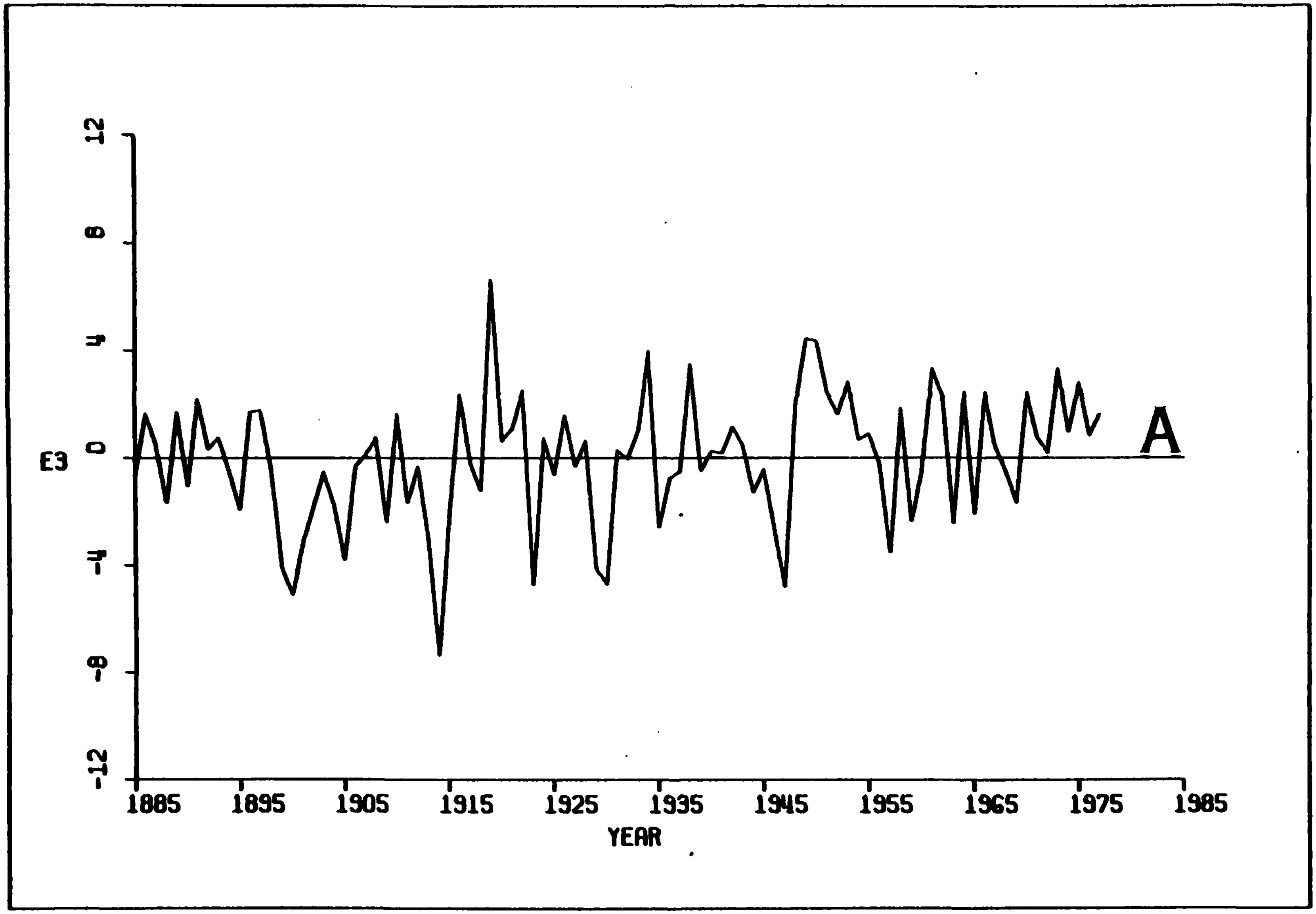

A
E3
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9A-3

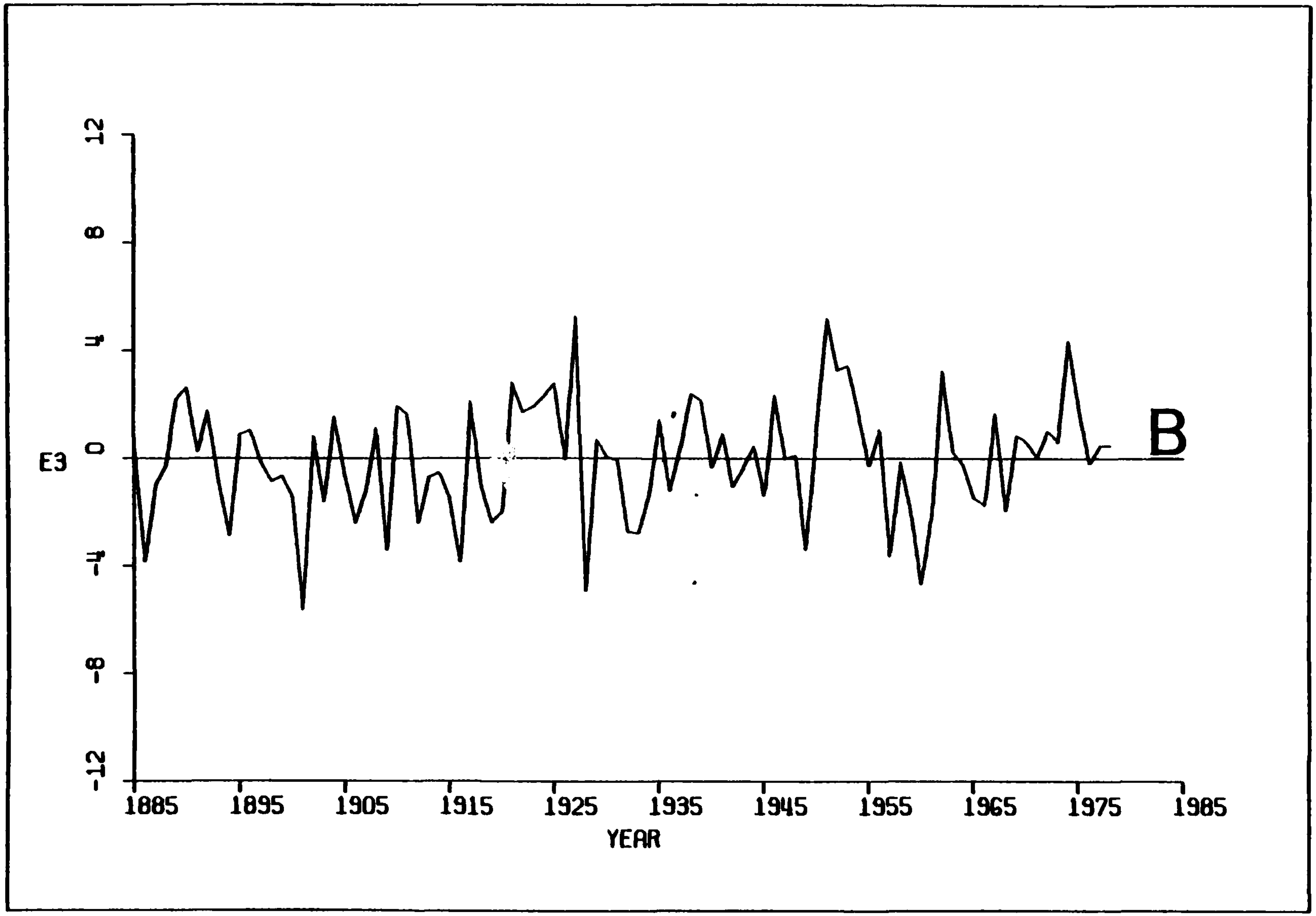

B
E3
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9B-2

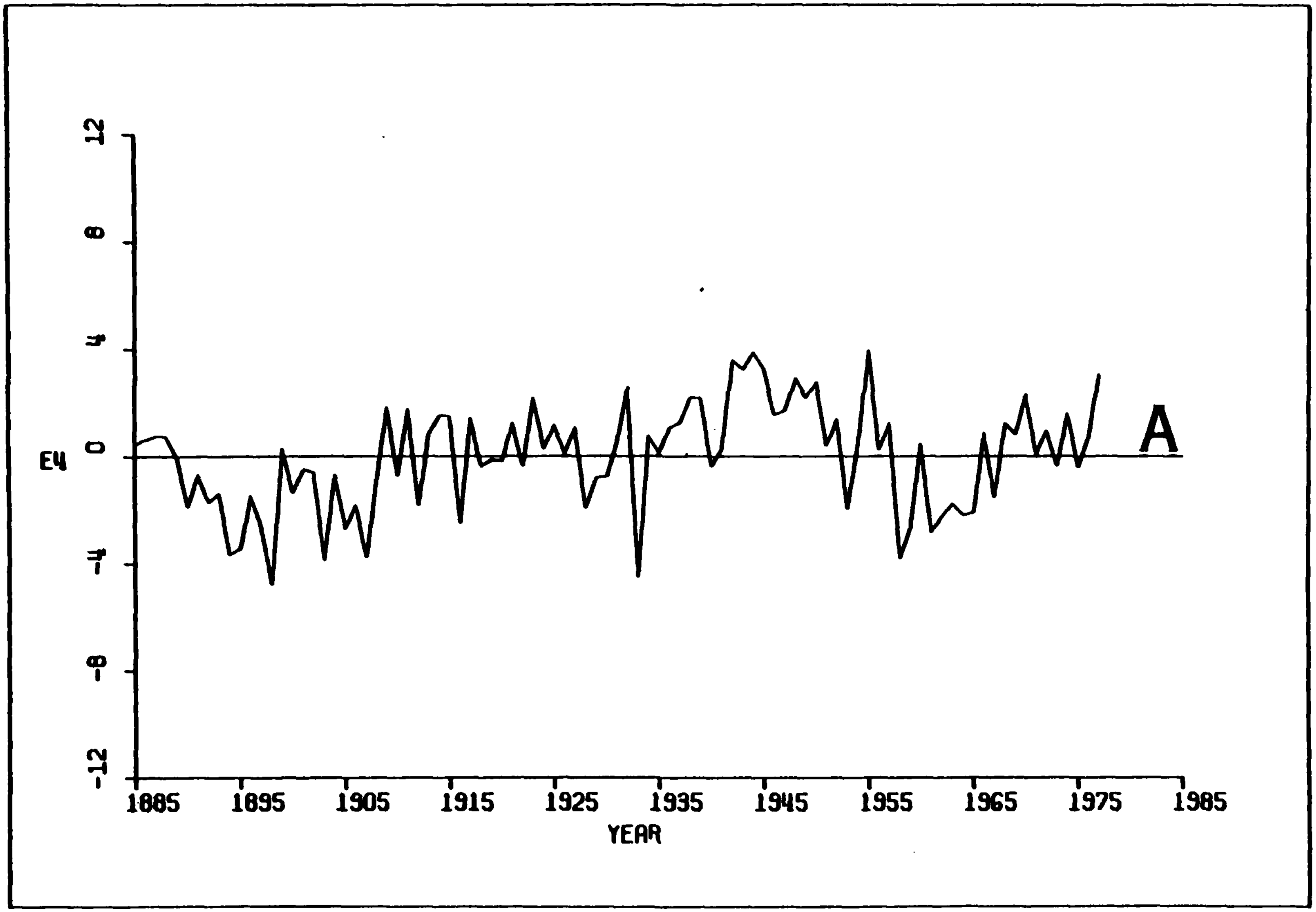

A
E4
12
8
4
0
-4
-8
-12
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
YEAR

Fig. 9A

Fig. 9B-4

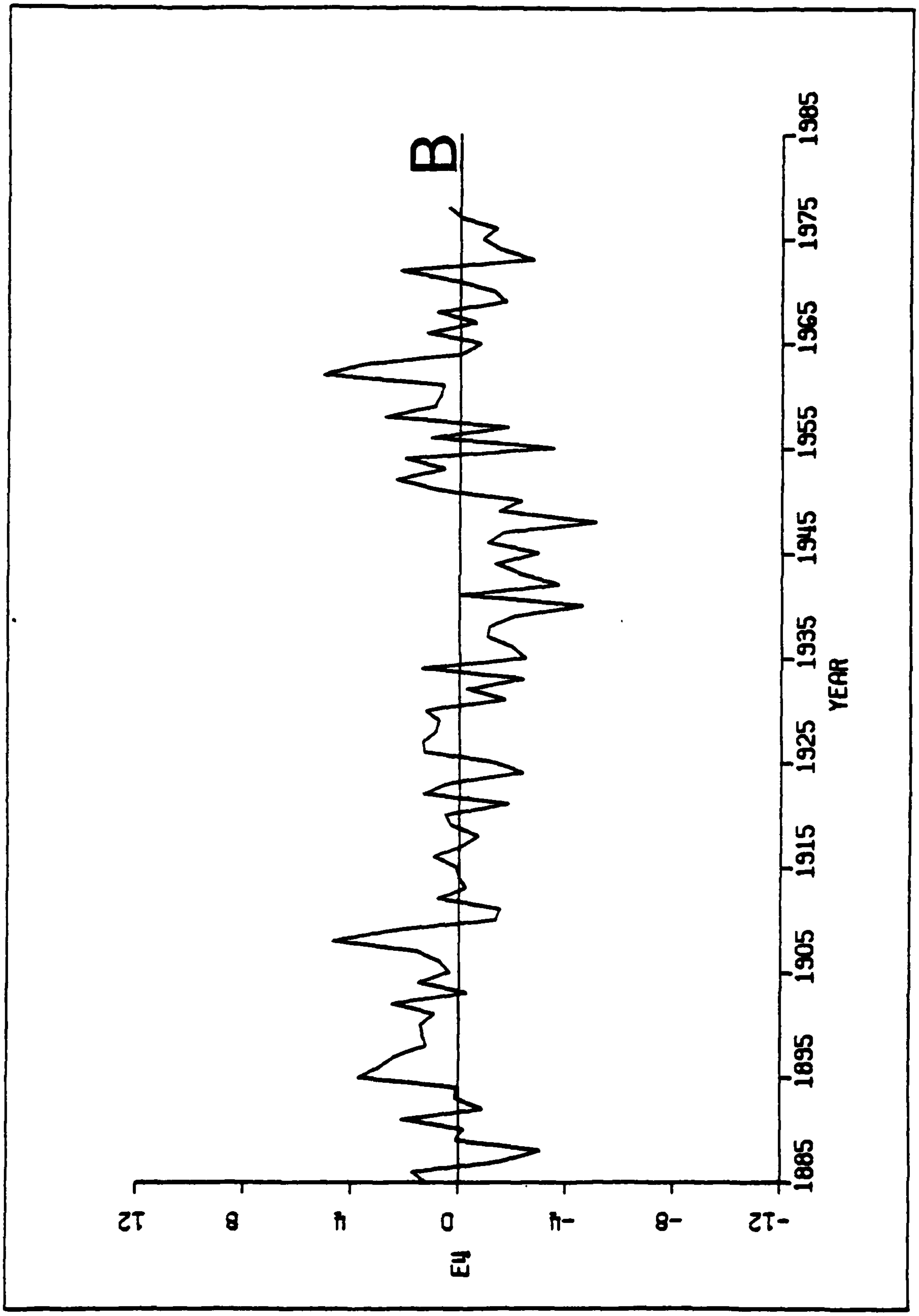
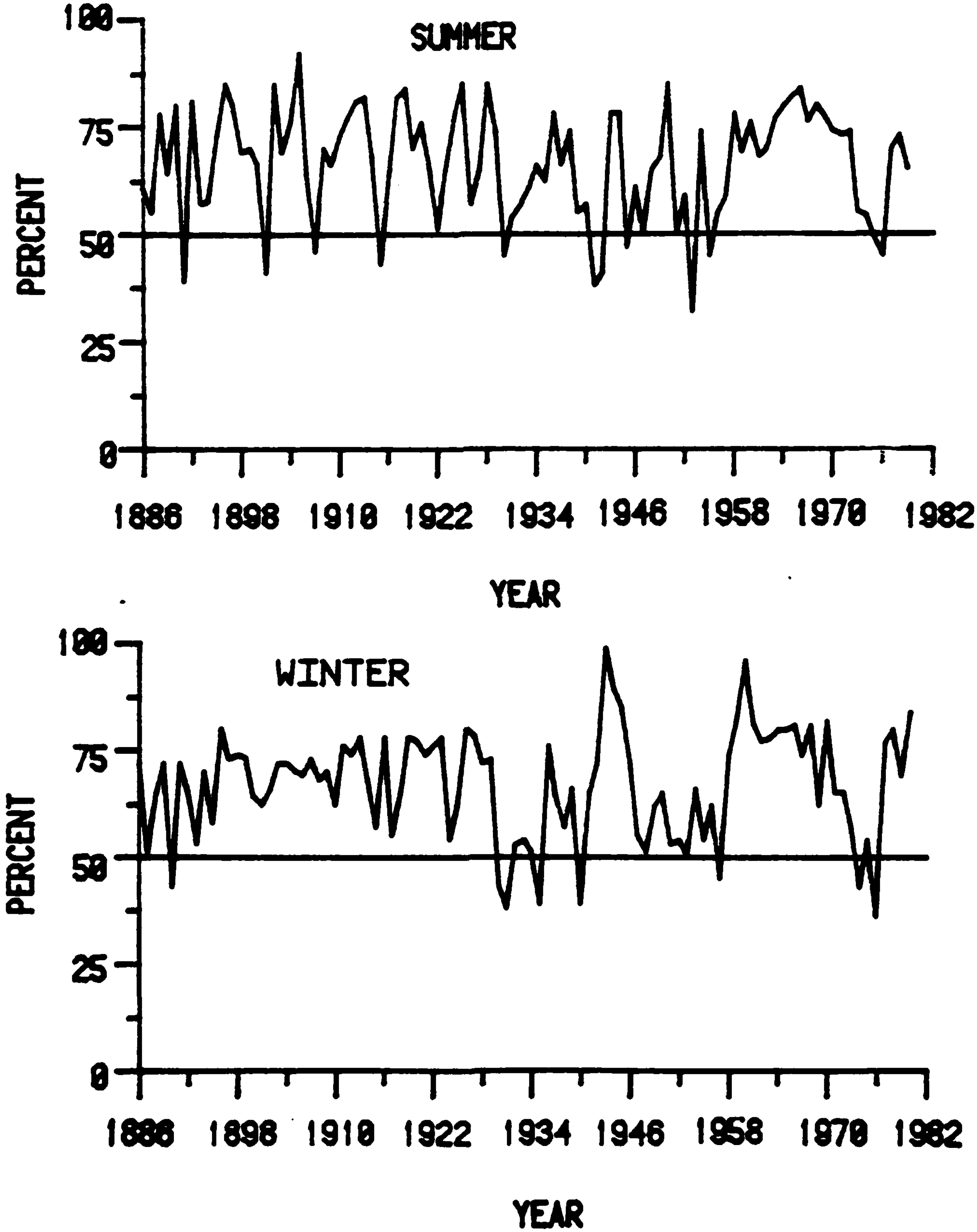
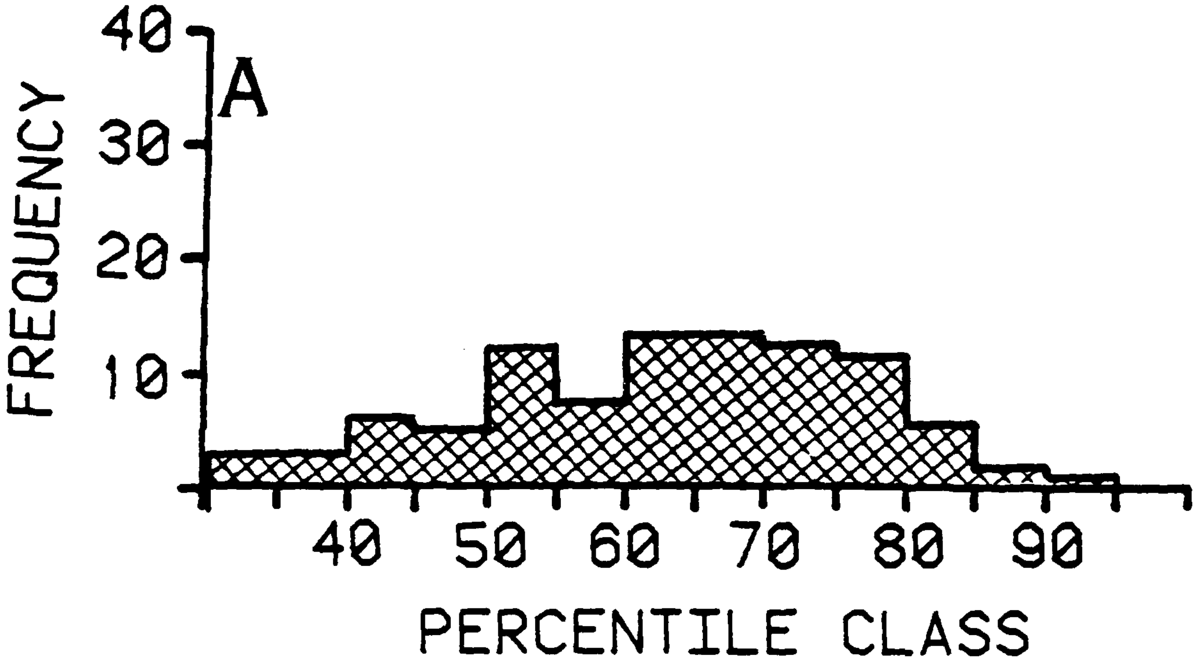

B
YEAR
1885
1895
1905
1915
1925
1935
1945
1955
1965
1975
1985
E4
12
8
4
0
-4
-8
-12

Fig. 10

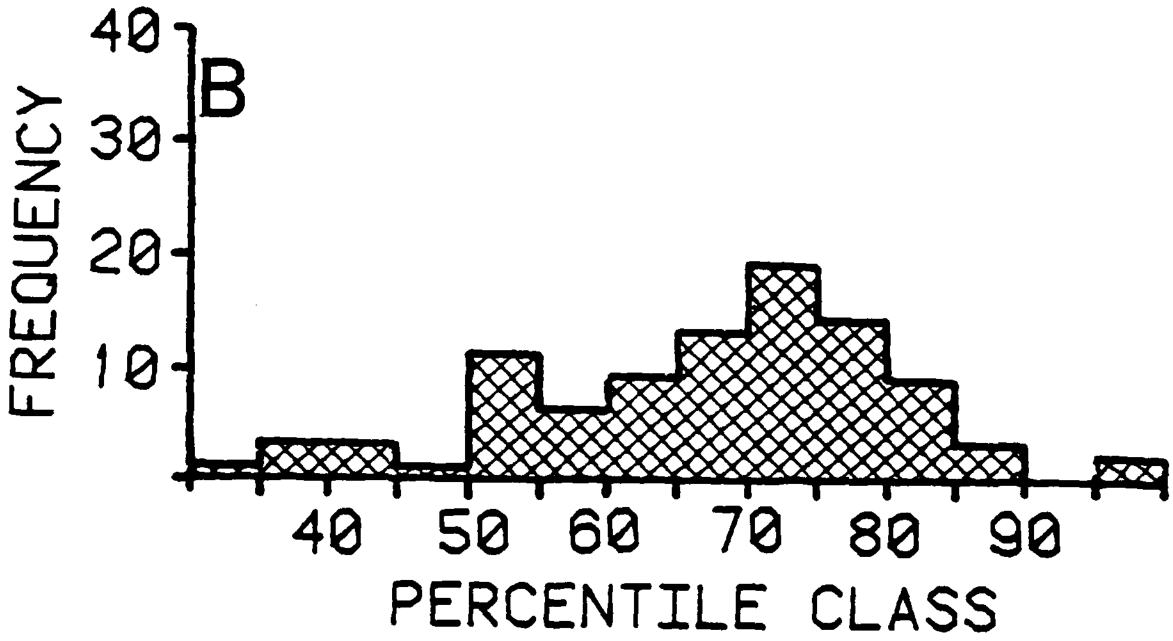


SUMMER
PERCENT
100
75
50
25
0
1886 1898 1910 1922 1934 1946 1958 1970 1982
YEAR
WINTER
PERCENT
100
75
50
25
0
1886 1898 1910 1922 1934 1946 1958 1970 1982
YEAR

Fig. 11



40
30
20
10
FREQUENCY
A
40
50
60
70
80
90
PERCENTILE CLASS



40
30
20
10
FREQUENCY
B
40
50
60
70
80
90
PERCENTILE CLASS

Fig. 12

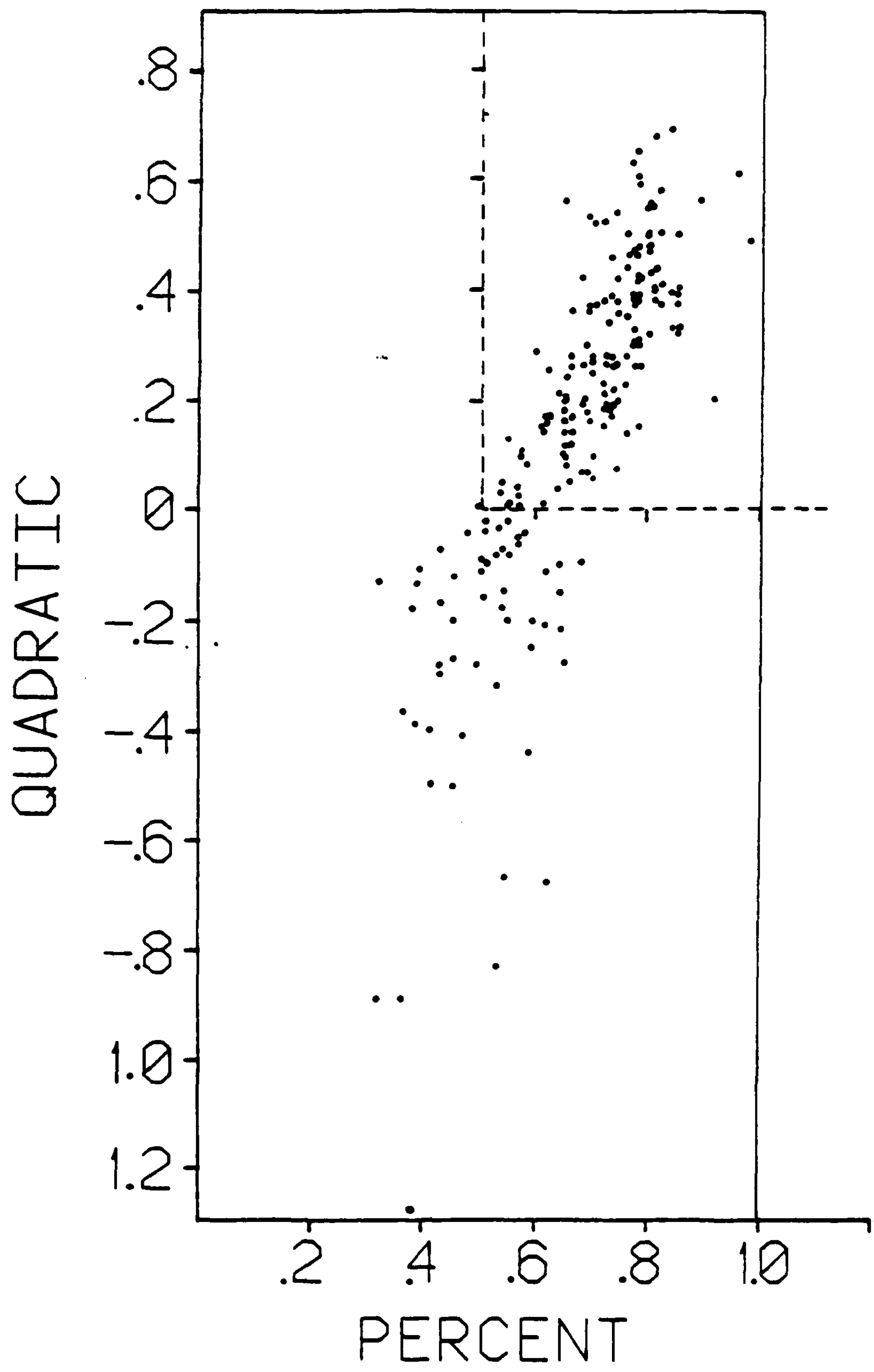


Fig. 13

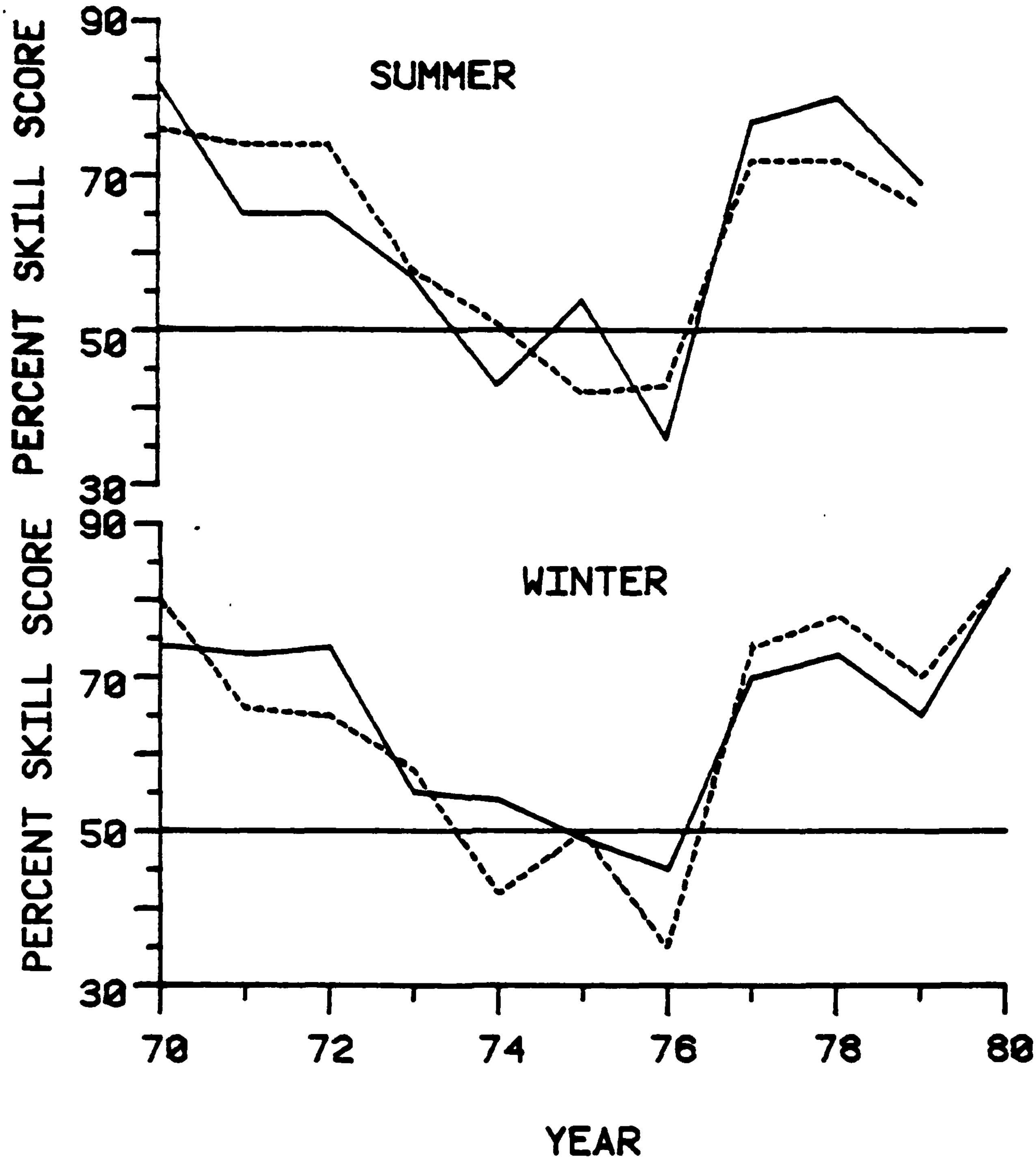
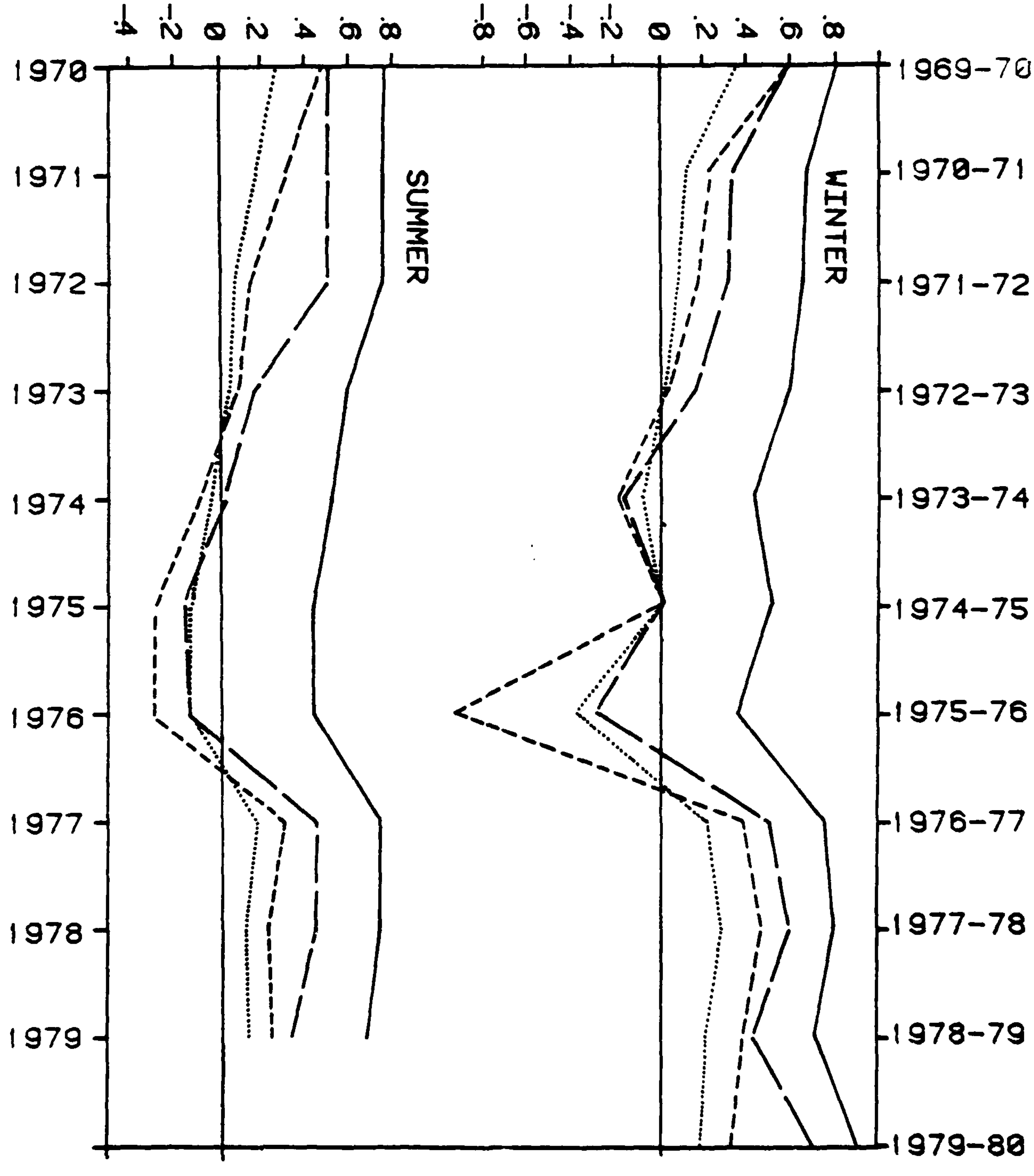
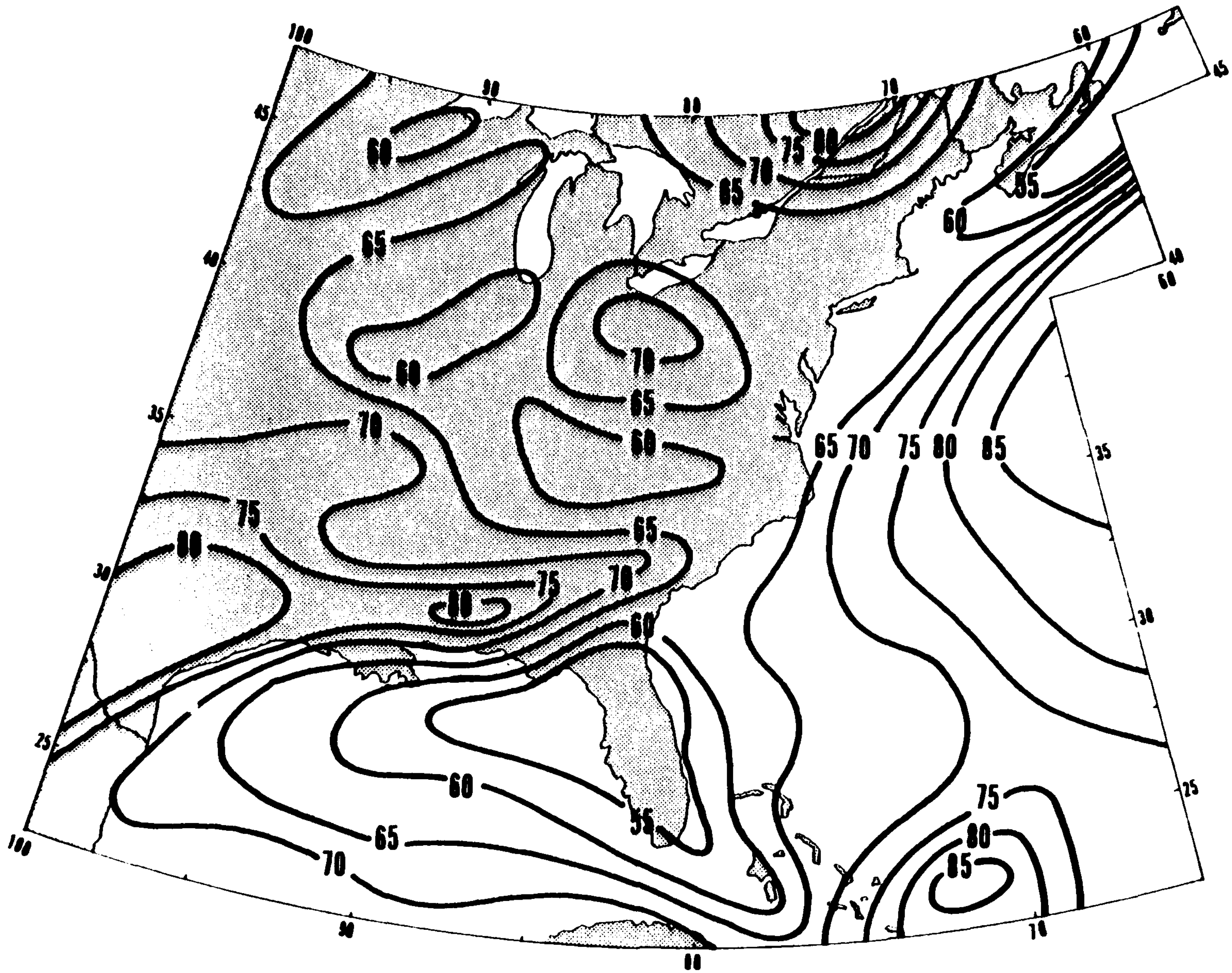

SUMMER
WINTER
PERCENT SKILL SCORE
PERCENT SKILL SCORE
90
70
50
30
90
70
50
30
70
72
74
76
78
80
YEAR

Fig. 14



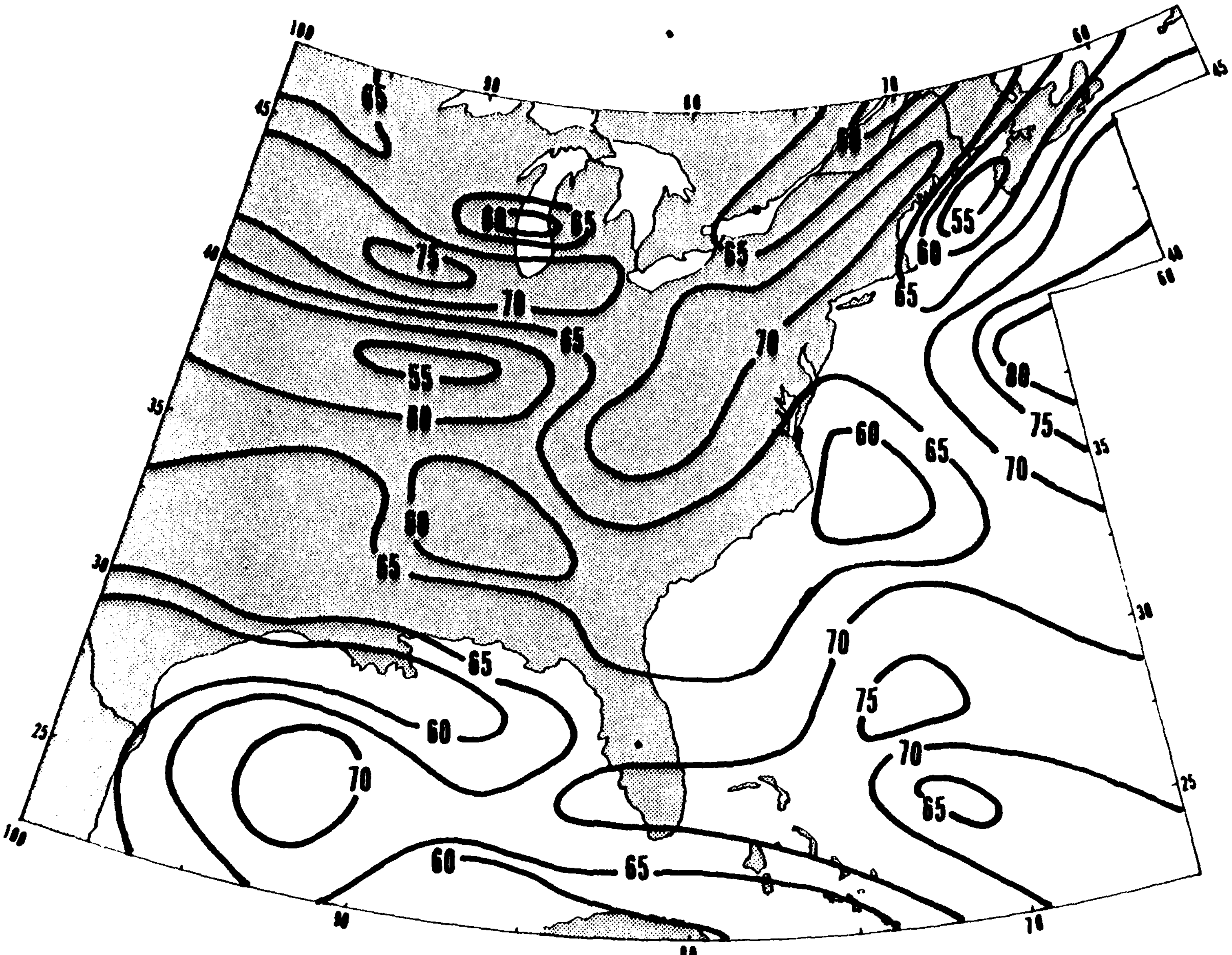
SUMMER
WINTER
1970
1971
1972
1973
1974
1975
1976
1977
1978
1979
1969-70
1970-71
1971-72
1972-73
1973-74
1974-75
1975-76
1976-77
1977-78
1978-79
1979-80
-.4
-.2
0
.2
.4
.6
.8
-.8
-.6
-.4
-.2
0
.2
.4
.6
.8



% SKILL FOR WINTERS

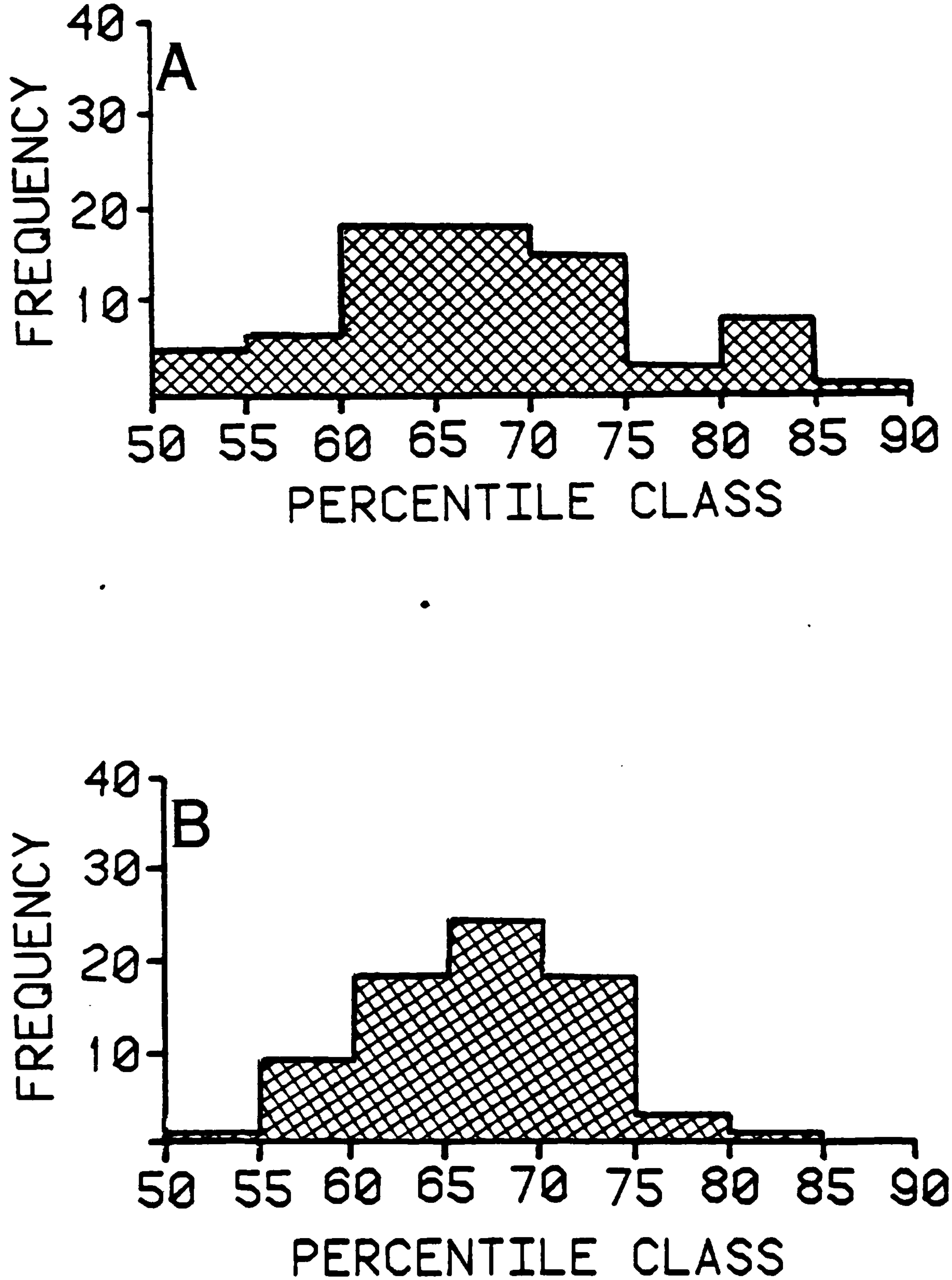
Fig. 15A

Fig. 15B



% SKILL FOR SUMMERS

Fig. 16


A
FREQUENCY
40
30
20
10
50 55 60 65 70 75 80 85 90
PERCENTILE CLASS
B
FREQUENCY
40
30
20
10
50 55 60 65 70 75 80 85 90
PERCENTILE CLASS

WINTER 1979/80

PREDICTED

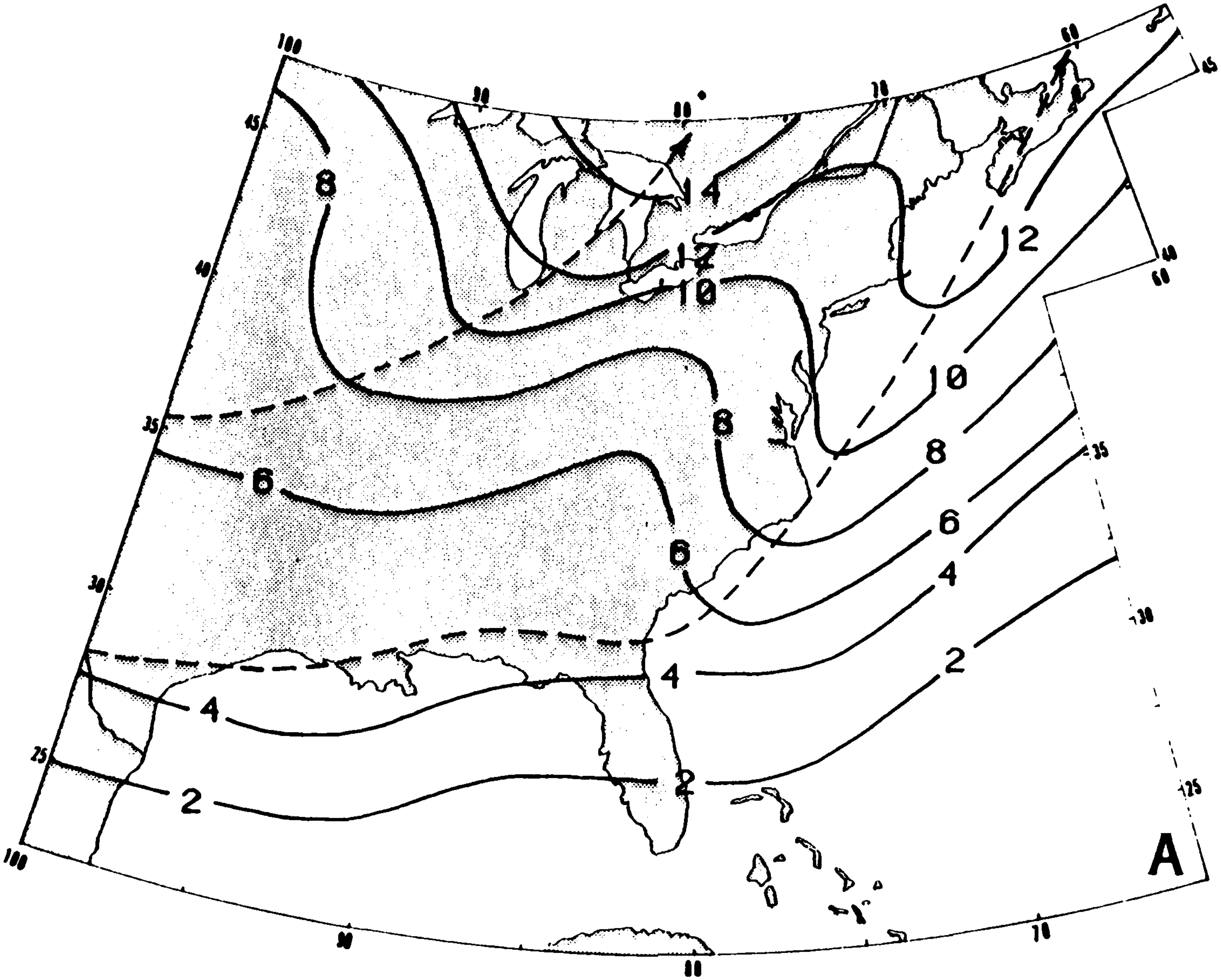


Fig. 17A

WINTER 1979/80
ACTUAL

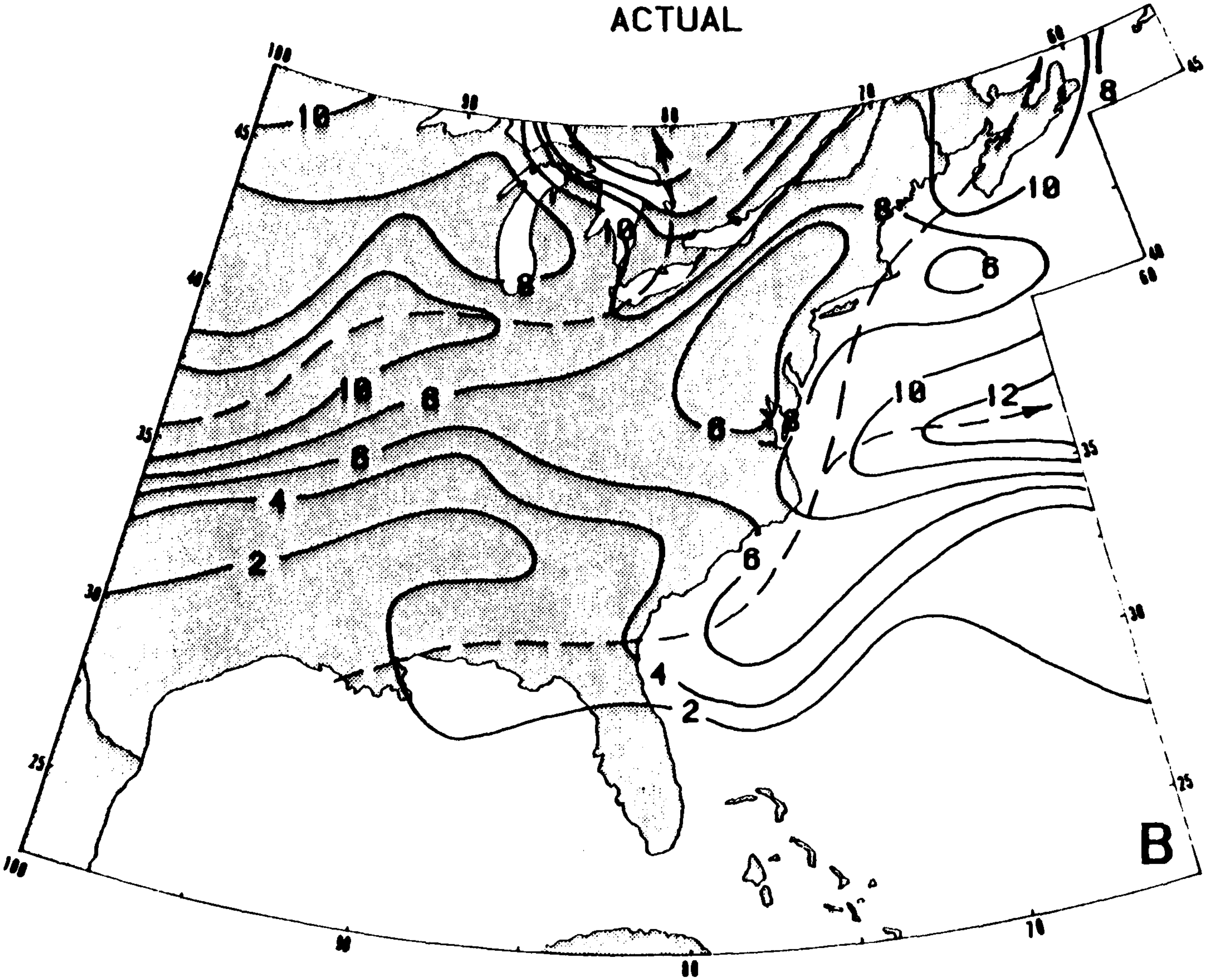


Fig. 17B

WINTER 1979/80
PREDICTED - MEAN

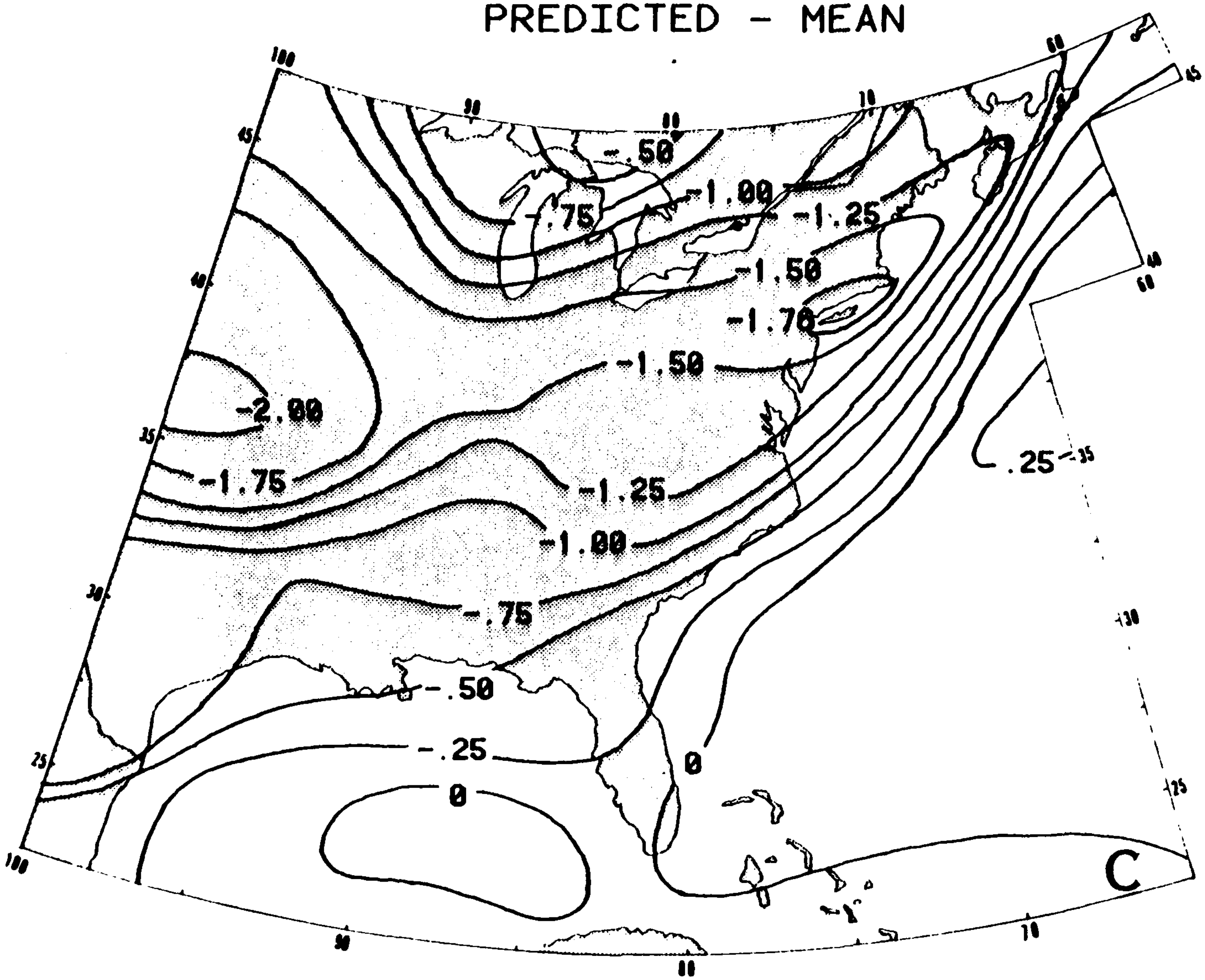


Fig. 17C

WINTER 1979/80

ACTUAL - MEAN

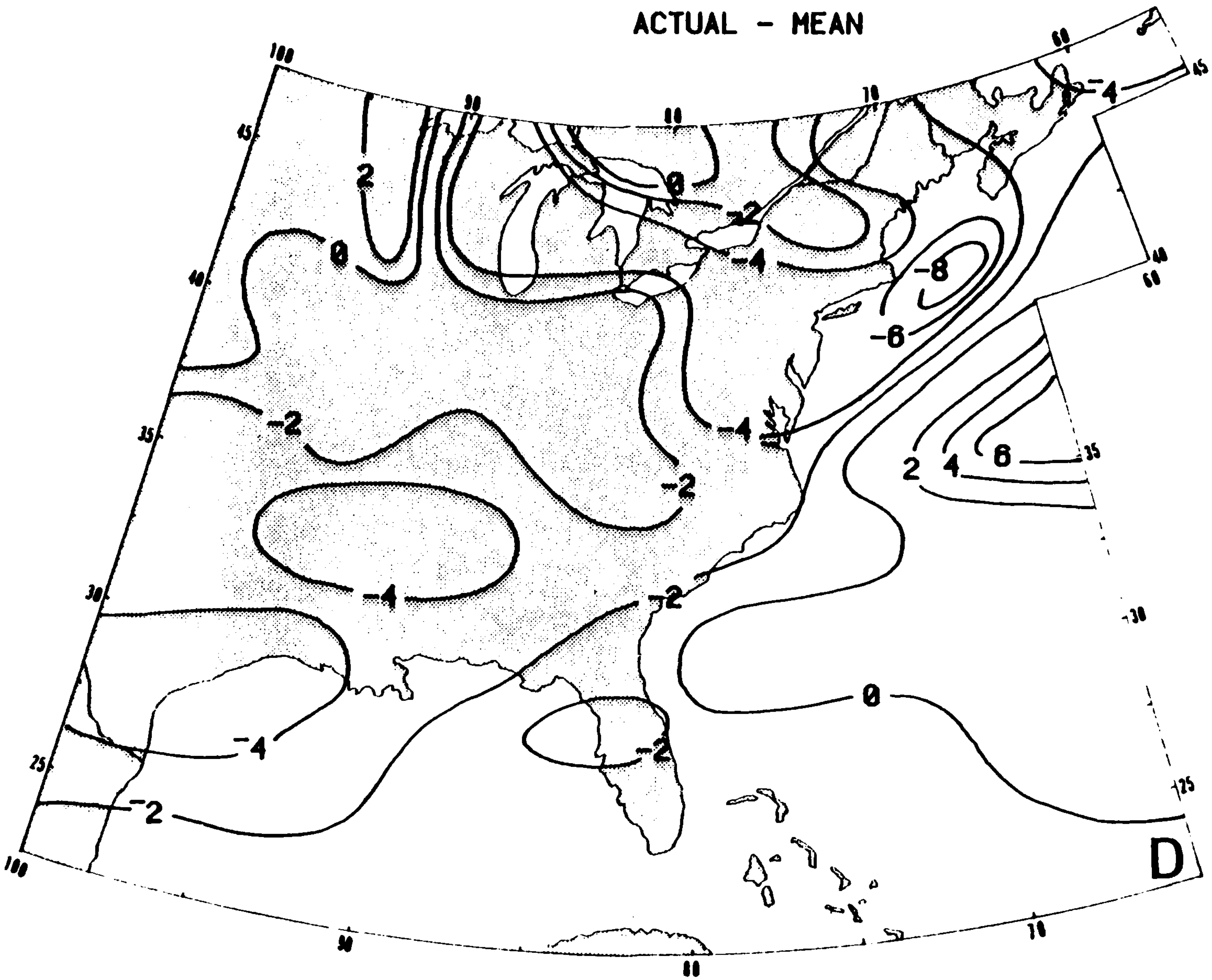


Fig. 17D

WINTER 1979/80

PREDICTED - ACTUAL

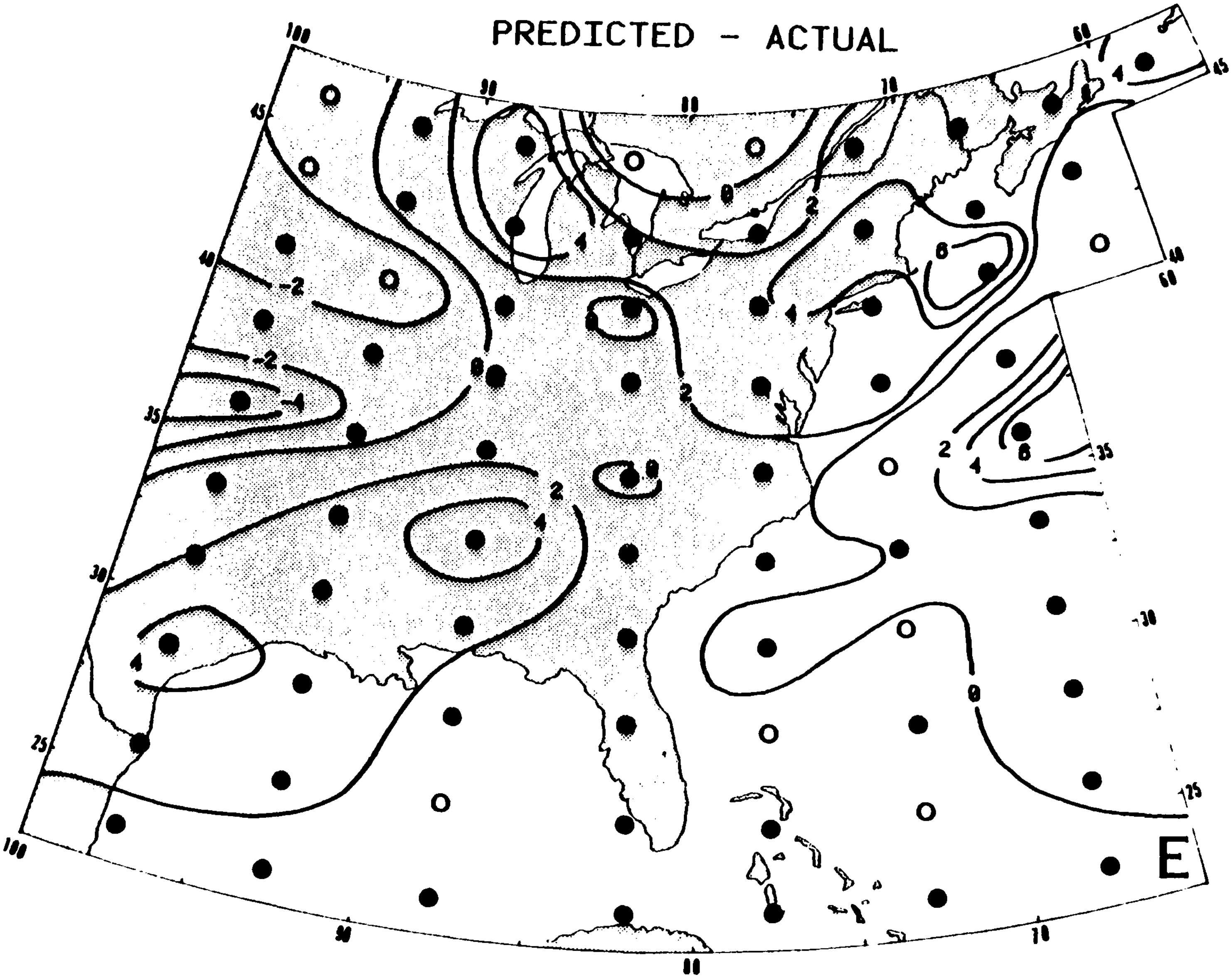


Fig. 17E

WINTER 1979/80
CYCLONE FREQUENCY FORECAST

% SKILL SCORE	84%
HEIDKE SKILL SCORE	68
DEVIATION SKILL SCORE	18
QUADRATIC SKILL SCORE	33

Fig. 17F

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Department of Environmental Sciences University of Virginia Charlottesville, Virginia 22903	Unclassified
	2b. GROUP Unclassified

3. REPORT TITLE

Season-to-Season Cyclone Frequency Prediction

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Bruce Hayden

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1980	37	53

8a. CONTRACT OR GRANT NO. N00014-81-K-0033	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 22
b. PROJECT NO. Project NR 389 170	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Geography Programs Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT

Winter and summer cyclone frequencies for eastern North America and the western North Atlantic were tabulated for 2.5^{o} latitude by 5^{o} longitude grid cells for the years 1885-1979. Correlation matrix eigenvectors were calculated for matrices of both the winter and summer data. The first four eigenvectors of each matrix are highly similar in form and the first, second and fourth eigen-vectors are highly correlated in the time domain. These correlations permit a season-in-advance estimation of cyclone frequencies. The multivariate prediction model developed is called the University of Virginia Climate Prediction Model. Forecast skill in both winter and summer averages 66% relative to the means as forecasts. Forecast failure (negative skill) occurs in about 8% of the winter forecasts and 11% of the summer forecasts. Positive skill relative to chance and persistence is also demonstrated.

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Climate prediction Cyclone frequency Storm prediction Statistical prediction						

Unclassified
Security Classification

Technical Report No. 23

SECULAR VARIATION IN ATLANTIC COAST EXTRATROPICAL CYCLONES

Bruce Hayden

Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

January 1981

Geography Programs
Office of Naval Research
Contract No. N00014-81-K-0033

Reprint from Monthly Weather Review
Vol. 109, No. 1, January 1981

Reprinted from MONTHLY WEATHER REVIEW, Vol. 109, No. 1, January 1981
American Meteorological Society
Printed in U. S. A.

Secular Variation in Atlantic Coast Extratropical Cyclones

BRUCE P. HAYDEN

Department of Environmental Sciences, University of Virginia, Charlottesville 22903

(Manuscript received 11 December 1979, in final form 10 July 1980)

ABSTRACT

To define spatial and temporal variations in annual cyclone frequencies, principal components were calculated from a matrix of annual frequencies for 74 grid cells covering eastern North America and the western North Atlantic and the years 1885 to 1978. The first principal component contrasts cyclone frequencies in continental versus marine areas. Since the early years of this century, there has been a trend toward increased cyclone frequency over marine areas and a decline in frequencies over the continent. This trend peaked in the 1960's. The second principal component is interpreted as an east coast cyclogenesis function. Like the first component, it exhibits a century-long secular variation with increasing coastal cyclogenesis in recent decades and a maximum in the 1950's. The first two components explain 45% of the total variance. Higher order vectors (3rd and 4th) explained 12% of the variance and geographically depict variance in the Gulf coast and Great Lakes regions, respectively. Secular variations in the weightings of the third and fourth components contain higher frequency variations than the first and second components.

1. Introduction

Damaging waves and storm surges along the U.S. Atlantic coast are largely due to extratropical cyclones. Along most of this coast, shorelines are receding (Hayden *et al.*, 1979; Dolan *et al.*, 1979). The erosion trend is attributed to the current rise in sea level (Bruun, 1962), lower average cyclone central pressure (Mather *et al.*, 1964), reduced coastal sand supply (Hoyt, 1967), human activities (Dolan *et al.*, 1973), and to secular variation in cyclone frequency, magnitude and duration (Hayden, 1975). More recently, changes in the movement of cyclones along the Atlantic coast have been reported (Resio and Hayden, 1975; Dickson and Namias, 1976). Changes in the track of cyclones relative to the coast give rise to variations in breaker heights and storm surge heights at the coast (Resio and Hayden, 1975).

The Resio and Hayden study is limited by the small reach of coast studied and the Dickson and Namias study by the short time span analyzed (1948–75). In this report, spatial and temporal variations in cyclone frequencies are examined for the years 1885 to 1978. The study area is eastern North America and the western North Atlantic east of the 100th meridian and south of the 50th parallel (Fig. 1).

2. Earlier work on cyclone frequencies

Petterssen (1950) mapped the geographical frequencies of cyclones in the Northern Hemisphere using daily sea level *Historical Weather Maps* for the period 1899–1939. Petterssen's maps show a frequency maximum along the east coast of the United States as far south as Florida. Klein and Winston (1958) attribute the east coast cyclone frequency maximum to an Atlantic seaboard cyclone track. Cyclogenesis associated with this track occurs along the tier of Gulf coast states or along the Virginia Capes. Reed (1960) indicates in his maps of percentage frequency of fronts that the front-frequency maximum also parallels the east coast margin but at some distance offshore during the years 1952–56. Miller (1946) analyzed cyclogenesis for the mid-Atlantic coastal region and found two distinct types: Type A which form largely to the north of Cape Hatteras, North Carolina, and Type B which form to the south of Cape Hatteras. While seasonal variations in cyclone frequency, front frequency and track locations are discussed in some detail, temporal variations were not studied.

Hosler and Gamage (1956) studied U.S. cyclone frequencies in 5° latitudinal and longitudinal grid cells for the 50 years ending in 1955. They found no evidence in the annual means of periodicities, trends or shifts in regions of maximum frequency. Reitan (1974, 1979) updated Hosler and Gamage's work and reported a general decline in cyclone frequencies.

Recent studies of cyclones along the Atlantic coast have focused on the generation of potentially damaging waves and surges. Hayden (1975) showed

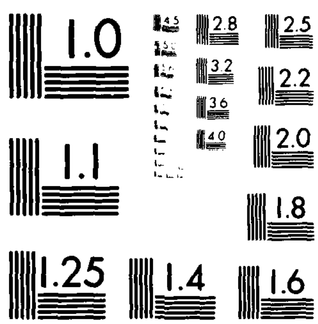
0027-0644/81/010159-09$06.25

AD-A098 581 VIRGINIA UNIV CHARLOTTESVILLE DEPT OF ENVIRONMENTAL --ETC F/G 4/2
SPATIAL AND TEMPORAL VARIATIONS IN CYCLONE FREQUENCY PATTERNS,(U)
APR 81 B P HAYDEN, R DOLAN, W SMITH N00014-81-K-0033

UNCLASSIFIED TR-21 NL

2 of 2
AD A
098581

END
DATE
FILMED
5-81
DTIC



MICROCOPY RESOLUTION TEST CHART

an increase in the frequency of storms that generate deep-water waves of 1.3 m or greater from 1942–67. Hayden concluded that the number, severity and duration of Atlantic coast storms had increased between 1942 and 1974. Increases in cyclone severity are also reported by Mather *et al.* (1964) and they attribute the changes to decreased central pressure between the 1920's and 1960's. Resio and Hayden (1975) found that cyclones moving along the U.S. Gulf coast and the genesis of new cyclones along the mid-Atlantic coast had increased from the 1920's to the 1960's. The pre-1920's period more closely resembled the 1960's than the years following the 1920's. Resio and Hayden also showed that the increased severity of Atlantic coastal storms resulted from a seaward displacement of mean storm tracks. They attributed this change to increased blocking in the high latitudes. Dickson and Namias (1976) identified blocking in the Greenland area and cooler than normal temperatures in the U.S. Southeast as the cause of increased frequencies of cyclones off the Atlantic coast between the 1940's, and the 1950's and 1960's.

3. The data

Cyclone frequencies for each year (1885–1978) were tabulated for the 74, 2.5° latitude by 5.0° longitude grid cells comprising the study area shown in Fig. 1. From monthly charts of the "Tracks of the Centers of Cyclones at Sea Level" published by the *Monthly Weather Review* and in recent years by *Mariners Weather Log*, annual totals of cyclones passing through each grid cell were recorded. Multiple entries of a given storm in a grid cell were ignored. Raw grid-cell frequencies were used rather than area-normalized frequencies, thus avoiding a latitude-dependent bias which can occur as a result of area normalization (Ballenzweig, 1959). A companion analysis was run on area-normalized data. The patterns of both the long-term means and standard deviations changed very slightly but the calculated principal components, percentages of variance explained, and time series of weightings were unchanged compared to analysis of raw frequency data. The resulting data matrix has the dimensions of 74 grid-cell variables and 94 annual cases.

4. Long-term means and variances

Fig. 2 shows the mean annual frequency of cyclones for the period 1885–1978. In general the frequency of cyclones increases with latitude and with proximity to the U.S. east coast. The axis of the east coast frequency maximum is centered over the coast from Nova Scotia to Georgia. The location of this frequency maximum coincides with the baroclinic zone separating the cold mainland from the warmer ocean waters.

The standard deviation of annual cyclone frequencies is presented in Fig. 3. The dominant feature shown by the chart is the pronounced frequency maximum offshore. The axis of this

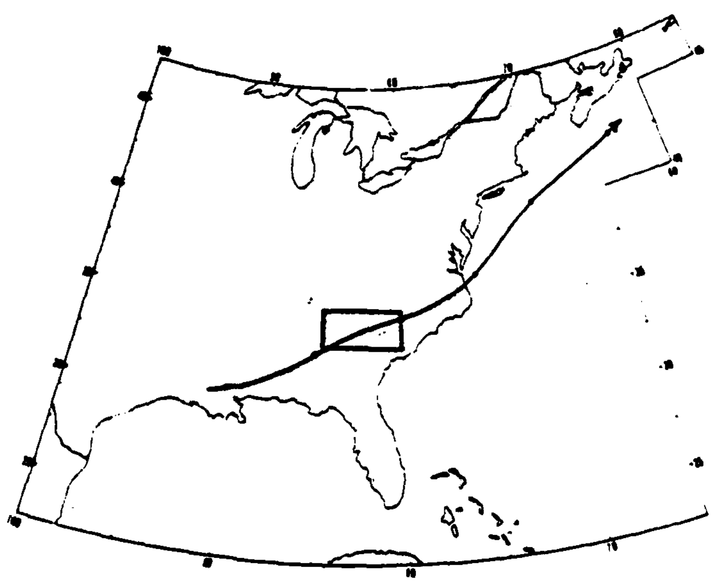


FIG. 1. Chart of the study area. The rectangular inset is 2.5° latitude × 5.0° longitude. There are 74 such rectangular grid cells in the study area. The arrow represents a storm track passing through the grid cell shown.

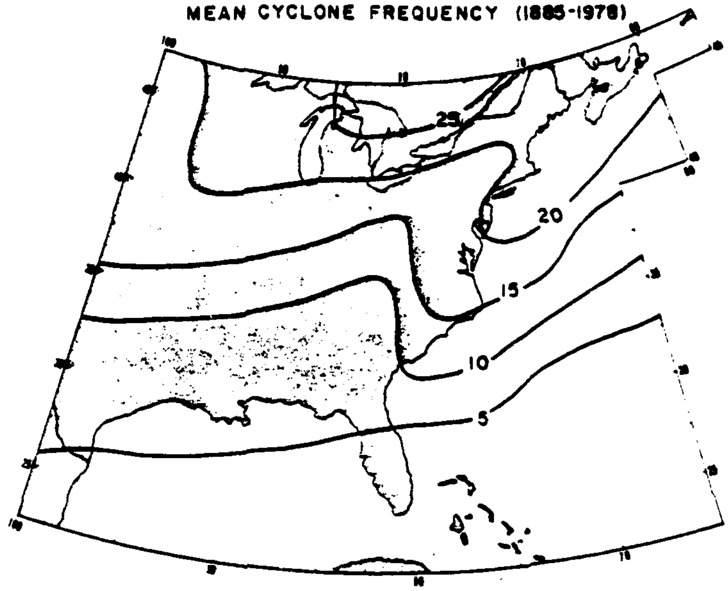


FIG. 2. Mean annual cyclone frequency for the years 1885–1978.

maximum is seaward of the maximum in the mean field (Fig. 2) and apparently rotated clockwise several degrees. The location of the standard deviation maximum more closely approximates the locus of the Gulf Stream than the continental margin. The standard deviations landward of the margin of the east coast are rather modest suggesting that the axis of yearly storm occurrences may expand eastward but in general not over the mainland.

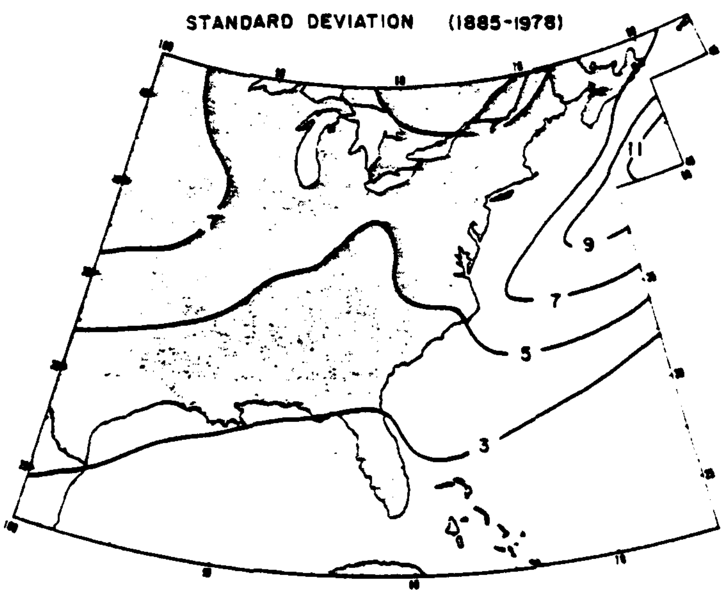


FIG 3. Standard deviations of the mean annual cyclone frequency for the years 1885–1978.

TABLE 1. The percentage of the total variance for the first four eigenvectors.

Eigenvector number	Percent variance explained	Cumulative percent variance explained
1	28.0	28.0
2	17.3	45.3
3	6.6	51.9
4	5.5	57.4

5. Principal component analysis of annual frequency data

a. The analysis

Principal component analysis has successfully resolved the variance structure in multivariant, geophysical data (Kutzbach, 1967; Fritts *et al.*, 1971; Resio and Hayden, 1975), and in terms of least square errors, this type of analysis provides a method for determining patterns in large data fields (Lorenz, 1956; Gilman, 1957; Kutzbach, 1967). The objective of the analysis is to isolate characteristic, recurrent, and independent modes of covariance among variables into a new set of independent variables. Basically, the analysis transforms a set of intercorrelated variables into a new coordinate system in which the axes are linear combinations of the original variables and are mutually orthogonal.

To prevent those grid cells with high mean cyclone frequencies (high latitudes) from dominating the total variance and consequently from dominating the eigenvector forms, the correlation matrix was used rather than the covariance matrix. The procedures for calculation of the eigenvectors follow those of Kutzbach (1967) and Vincent *et al.* (1976).

Principal component analysis provides a description of the major modes of variability in the data set. Typically, each component is identified with some property of the data field. The analysis also provides an index which measures the importance of each component within each year. Finally, the analysis provides an estimate of the total percent of variance in the data set which can be explained on the basis of each component.

b. The eigenvectors

The percentage of variance and the cumulative percentage of variance explained by the first four eigenvectors is given in Table 1. As indicated in the table the first four eigenvectors account for 57.4% of the total variance. The problem has thus been reduced from a 74-variable problem in which the variables are intercorrelated, to a 4-variable problem in which each new variable is orthogonal and thus statistically independent. Higher order eigenvectors explained smaller fractions of the total variance and are not dealt with here.

The eigenvectors corresponding to the eigenvalues 1 through 4 are mapped in Figs. 4–7. The first eigenvector (Fig. 4) indicates that the dominant mode of cyclone frequency variation about the mean is, with positive weightings, a relative abundance of cyclones over marine areas with diminished cyclone frequencies over the continent. Years with negative weightings would be characterized by relatively few cyclones over marine areas and above average frequencies over the continent. The corridor of positive values over marine areas shown in Fig. 4 corresponds in location to the zone of increased cyclone frequencies found by Dickson and Namias (1976) and the east and south displaced storm track identified by Resio and Hayden (1975). The first eigenvector suggests a negative teleconnection between offshore displacement of cyclones and the frequency of Colorado lows. Inspection of contoured cyclone frequency maps confirms the existence of this negative teleconnection. Thus secular variations in the frequency of offshore displacement of cyclones is out of phase with the frequency of Colorado lows.

The second eigenvector (Fig. 5) has positive values over the entire field and as such indicates for positively-weighted years, a general increase in cyclone numbers and in negatively-weighted years, fewer than average cyclones. The dominant feature of the map of eigenvector no. 2 is the maximum centered over the coast of the mid-Atlantic. This pattern is rather similar to the charts of cyclogenesis frequency published by Petterssen (1941 and 1956) and Reitan (1974). This suggests that the second principal component might best be termed a coastal cyclogenesis function.

The positive sense of the third eigenvector (Fig. 6) contrasts above-normal frequencies of storms moving eastward from the Great Plains up to the Ohio Valley and exiting the coast between Cape Hatteras and Cape Cod, with below normal frequencies of cyclones in the Gulf coast region. The fourth eigenvector (Fig. 7) contrasts the frequency of cyclone occurrence in the Great Lakes-Saint Lawrence River region with the frequency of cyclones moving out of the Great Plains. In years with positive weightings, storms are more frequent than average in southeastern Canada. Negatively-weighted years show an increase in storm frequency in the Colorado storm track area.

The first four eigenvectors of annual cyclone frequencies constitute four new orthogonal axes which account for nearly 60% of the variance in the original data. In general, weightings on these four vectors for the 93 individual years of record varied from −10 to +10. The meanings of each of the four new axes are summarized in Fig. 8.

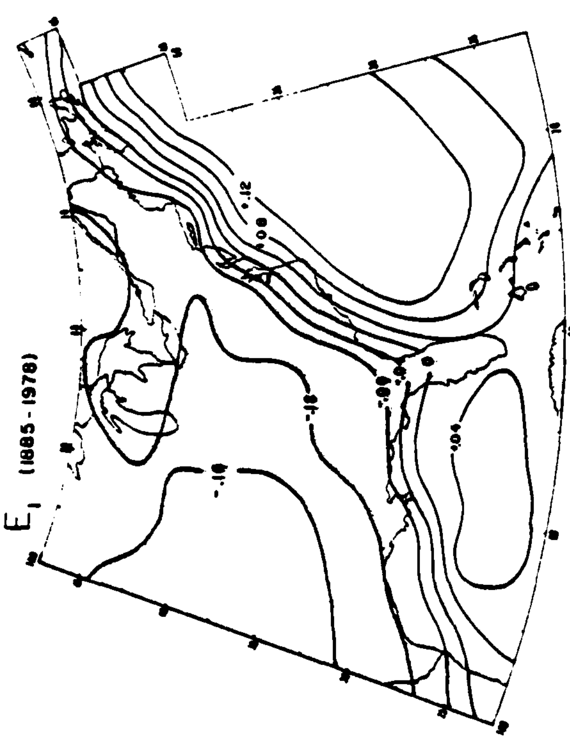


FIG. 4. The first eigenvector of annual cyclone frequencies.

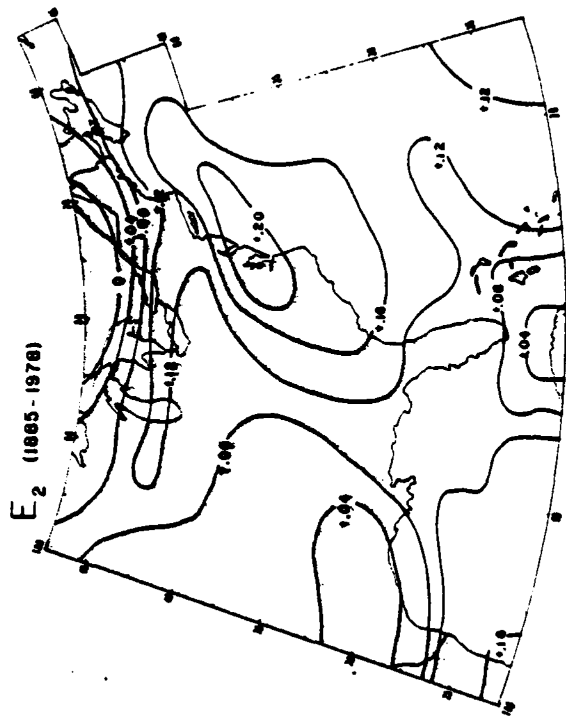


FIG. 5. The second eigenvector of annual cyclone frequencies.

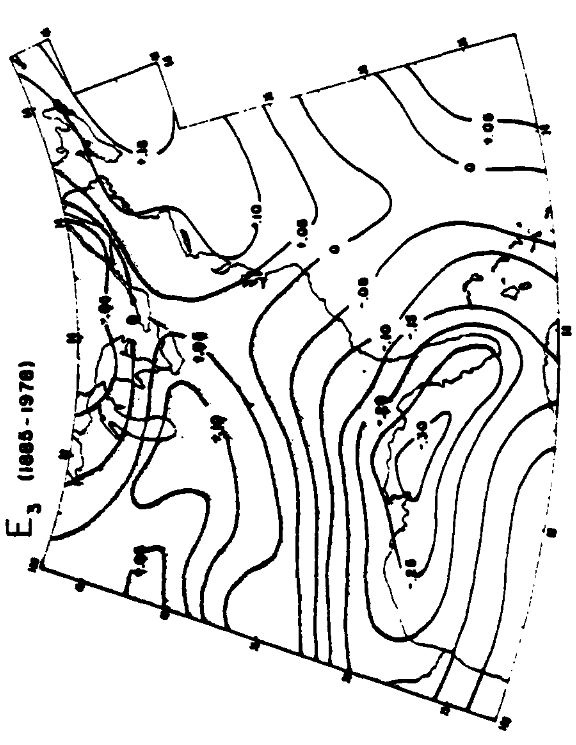


FIG. 6. The third eigenvector of annual cyclone frequencies.

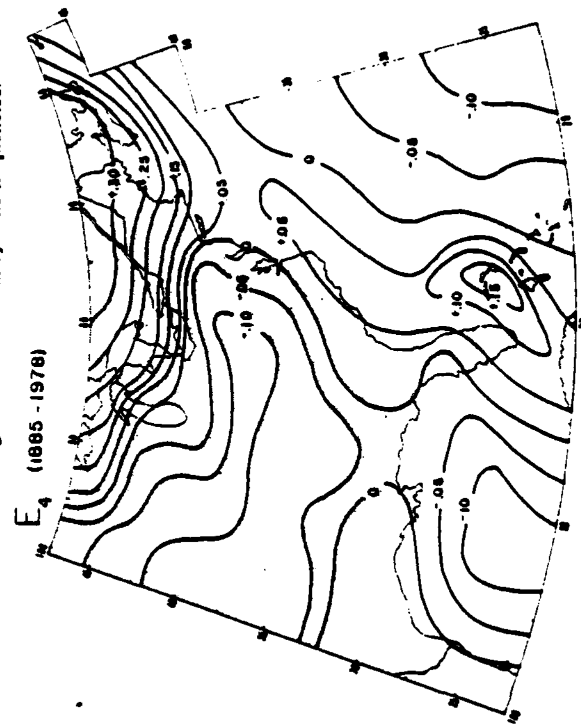


FIG. 7. The fourth eigenvector of annual cyclone frequencies.

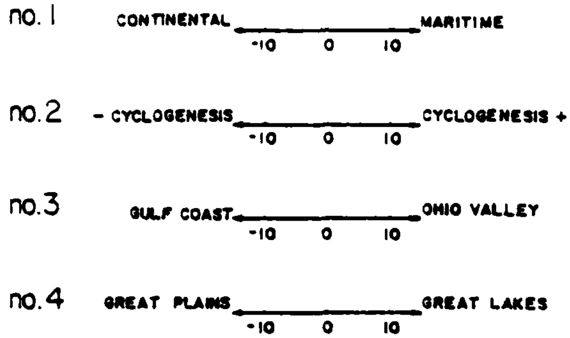


FIG. 8. Summary of the locations of cyclone numbers in excess of the mean for each of the first four eigenvectors. The − sign and the − sign associated with cyclogenesis for axis no. 2 indicates below and above normal cyclone numbers in the region of coastal cyclogenesis along the U.S. mid-Atlantic coast.

c. The time series

The time series of eigenvector weightings for each year (1885–1978) for each of the first four eigenvectors is shown in Figs. 9–12. The annual weightings of the first eigenvector show a broad quasi-sinusoidal variation of period slightly greater than 100 years. This variation thus suggests that cyclone frequencies declined over marine areas and increased over the continent between 1885 and 1925. Since 1925, cyclone frequencies over marine areas have increased and frequencies over the continent have declined. With the limited time series length it is not possible to establish whether the variation is indeed periodic.

Annual weightings of the second eigenvector (Fig. 10) also exhibit a century-long scale of variation from negative values at the beginning of the time series to positive values after 1910 and apparently back to negative values around 1960. If the interpretation of eigenvector 2 as representing coastal cyclogenesis is correct, then there should have been an increase in coastal cyclogenesis during the first four decades of the 20th century. This conclusion is consistent with the work of Hosler and Gamage (1956) and Reitan (1979). The secular variation shown in Fig. 9 is remarkably similar to that shown by Reitan (1979) in annual cyclone totals (his Fig. 3). Reitan (1979) notes that about 30% of the decline in cyclone frequency since 1950 is due to decreased cyclogenesis. The early 1940's minimum of cyclone totals reported by Reitan (1979) is clearly evident in the time series weighting of the second principal component (Fig. 9).

The secular variation evident in Figs. 9 and 10 raises questions about the detectability of cyclones off the U.S. Atlantic coast in the early portion of the record. Examination of year-by-year cyclone frequency charts shows a scarcity of cyclones over the continent of the same order in recent decades as over the oceanic areas earlier in the century. Resio and Hayden (1975) used 1899–1970 hemispheric pressure data to reconstruct mid-Atlantic coast cyclone frequencies. This synthetic record for cyclones migrating from inland and forming along the coast shows a minimum in the 1920's and a maximum in the 1960's similar to those shown in Figs. 9 and 10.

To determine whether an observational insufficiency in marine areas in the early years of record would account for the secular trend shown in Fig. 9 a reduced data matrix was analyzed. All grid cells south of 27.5°N and east of 70°W were removed and the principal components were calculated. There were essentially no differences in the resulting components or time series of weightings. The percentage of variance explained by the first four components increased 2%. The first eigenvector for the reduced data matrix is shown in Fig. 13. The similarity to Fig. 4 is unmistakable. Clearly the shape of the eigenvector is not changed by changing the size of the data matrix or the removal of marine grid cells from the data. There seems to be no systematic observational insufficiency associated with the marine areas of the data field. The highest weightings in the first vector (Fig. 4) are not found in the middle of the grid as suggested by Buell (1975). Changing the grid size did not alter the pattern. The secular trends then must be considered real and not observational or mathematical artifacts.

The time series of the third and fourth eigenvectors (Fig. 11 and Fig. 12) show excursions from positive to negative weightings over shorter periods of years. The third eigenvector runs from negative values to positive values between 1900 and 1925, 1925 and 1950 and between 1955 and 1978. Spectral analysis shows some concentration of spectral power at about 23 years. The fourth eigenvector shows a broad decline from positive values in the early part of the record to low values in the late 1940's. Since the 1940's weightings have again increased.

The original data matrix was divided into a winter (October–March) and a summer (April–September) half. Principal components were calculated. This analysis was done to insure that the annual cyclone frequency principal components were not meaningless summations of winter and summer conditions. The forms of each set of principal components were very similar to those shown in Figs. 4 through 7 and the time series weightings were remarkably similar to those shown in Figs. 9 through 12. It appears that the main time scale of variation is extra- rather than inter-annual.

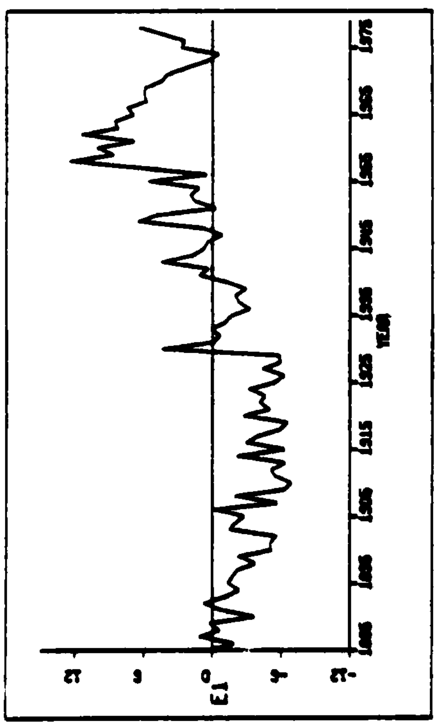


FIG. 9. Time variation of the annual weightings of the first eigenvector (E_1).

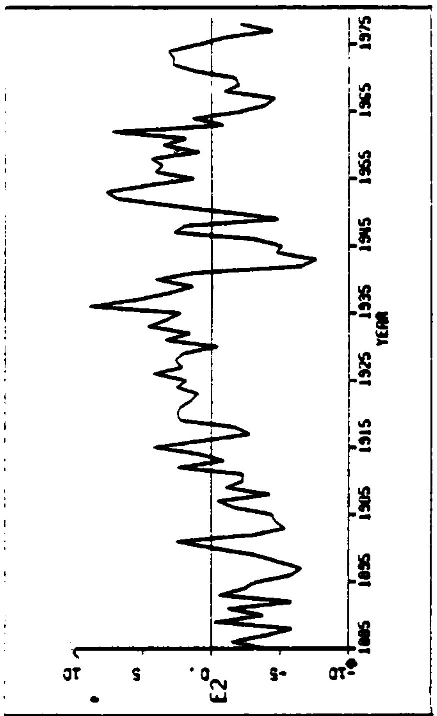


FIG. 10. Time variation of the annual weightings of the second eigenvector (E_2).

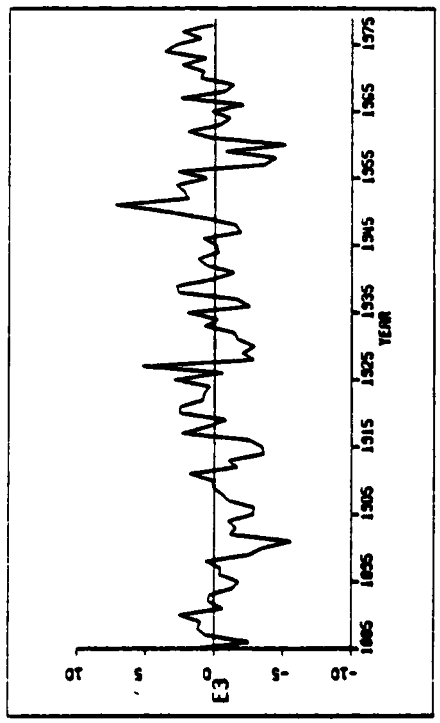


FIG. 11. Time variation of the annual weightings of the third eigenvector (E_3).

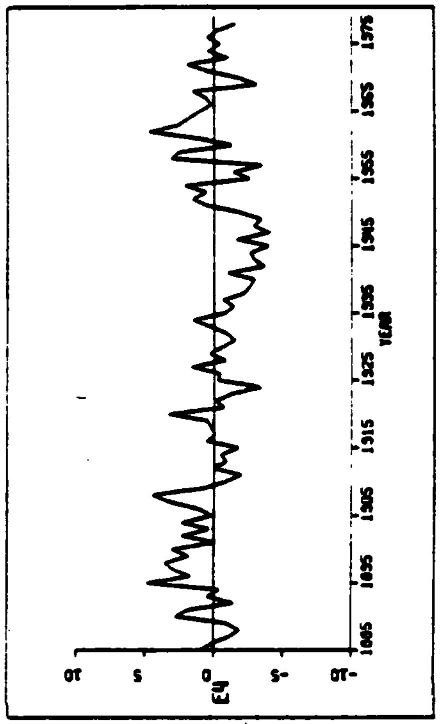


FIG. 12. Time variation of the annual weightings of the fourth eigenvector (E_4).

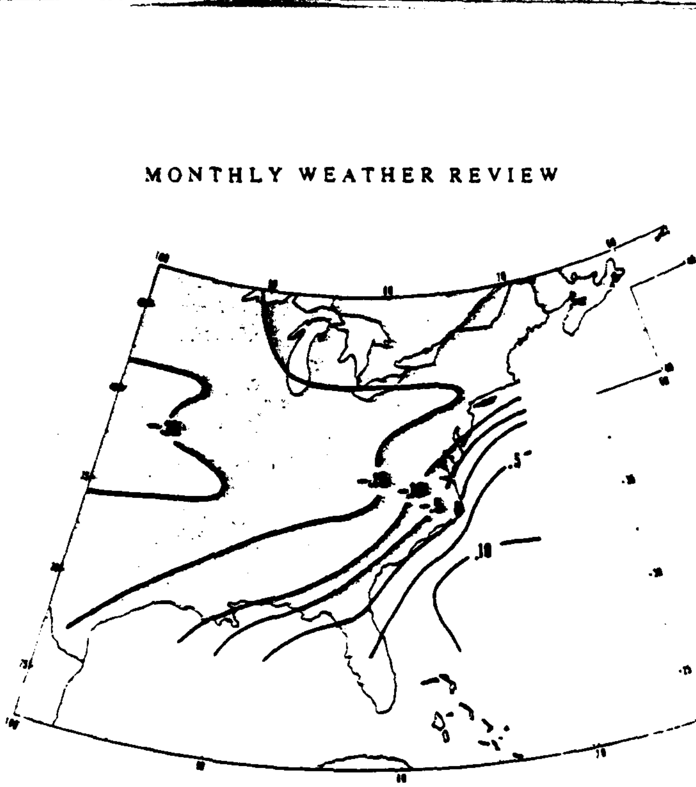


FIG. 13. The first eigenvector of annual cyclone frequencies for a reduced data matrix. The latitude limits of the data field are 27.5°N and 47.5°N. The longitude limits are 70°W and 100°W.

6. Discussion and conclusion

The variance in cyclone frequency is maximum off the U.S. Atlantic coast. Much of this variance is due to the eastward displacement of storm tracks that parallel the coast and to cyclogenesis along the mid-Atlantic portion of the east coast. Both of these two contributions to the total variance exhibit century-long secular variation. These changes are undoubtedly due to changes in the intensity of the east coast baroclinic zone and to shifts in the North American long-wave location associated with blocking in the high latitudes as suggested by Resio and Hayden (1975) and Dickson and Namias (1976).

It thus appears that the increased storminess of the U.S. east coast since the early 1940's (Mather *et al.*, 1964; Hayden, 1975; Resio and Hayden, 1975; Dickson and Namias, 1976) is part of a secular variation of a longer time scale. While the motivation for this study was the apparent increase in east coast damaging cyclones during this century, the results of the study have wider significance. In general, we may conclude that there have been several secular variations in cyclone frequency patterns: 1) declines in the frequency of Colorado lows have been associated with increases in cyclones off the Atlantic coast; 2) a general decline in cyclone frequencies is accompanied by a decline in cyclogenesis along the mid-Atlantic coast.

Acknowledgments. This work was supported by a grant from the Office of Naval Research (Contract N00014-75-C-0480). I wish to thank Jerome Namias for his valuable comments on this work, Robert Dolan for his careful review of the manuscript and Stephanie Lent for her efforts in processing the data.

REFERENCES

Ballenzweig, E. M., 1959: A practical equal-area grid. *J. Geophys. Res.*, **64**, 647–651.

Buell, C. E., 1975: The topography of the empirical orthogonal functions. *Preprints Fourth Conf. Probability and Statistics in Atmospheric Sciences*, Tallahassee, Amer. Meteor. Soc., 188–193.

Bruun, P., 1962: Tracing of material movement on seashores. *Shore and Beach*, **30**, 10–15.

Dickson, R., and J. Namias, 1976: North American influences on the circulation and climate of the North Atlantic sector. *Mon. Wea. Rev.*, **104**, 1255–1265.

Dolan, R., P. Godfrey, and W. Odum, 1973: Man's impact on the barrier islands of North Carolina. *Amer. Scient.*, **61**, 152–162.

——, B. Hayden, C. Rea, and J. Heywood, 1979: Shoreline erosion rates along the middle Atlantic coast of the United States. *Geology*, **7**, 602–606.

Fritts, H., T. Blasing, B. Hayden, and J. Kutzbach, 1971: Multivariate techniques for specifying tree growth and climate relationships and for reconstructing anomalies in paleoclimate. *J. Appl. Meteor.*, **10**, 845–864.

Gilman, D., 1957: Empirical orthogonal functions applied to thirty-day forecasting. Sci. Rept. No. 1, Dept. of Meteor., MIT, 120 pp. [NTIS AD117249].

Hayden, B., 1975: Storm wave climates at Cape Hatteras, North Carolina: Recent secular variations. *Science*, **190**, 981–983.

——, R. Dolan, and W. Felder, 1979: Spatial and temporal analyses of shoreline variations. *Coastal Eng.*, **2**, 351–361.

Hosler, C. L., and L. A. Gamage, 1956: Cyclone frequencies in the United States for the period 1905 to 1954. *Mon. Wea. Rev.*, **84**, 388–390.

Hoyt, J., 1967: Barrier island formation. *Geol. Soc. Amer. Bull.*, **78**, 1125-1136.

Klein, W. H., and J. S. Winston, 1958: Geographical frequency of troughs and ridges on mean 700 mb charts. *Mon. Wea. Rev.*, **86**, 344-358.

Kutzbach, J., 1967: Empirical eigenvectors of sea-level pressure, surface temperature and precipitation complexes over North America. *J. Appl. Meteor.*, **6**, 791-802.

Lorenz, E., 1956: Empirical orthogonal functions and statistical weather prediction. Sci. Rep. No. 1, Dept. of Meteor., MIT, 49 pp. [NTIS AD110268].

Mather, J., H. Adams, and G. Yoshioka, 1964: Coastal storms of the eastern United States. *J. Appl. Meteor.*, **3**, 693-706.

Miller, J., 1946: Cyclogenesis in the Atlantic coastal region of the United States. *J. Meteor.*, **3**, 31-44.

Petterssen, S., 1941: Cyclogenesis over southwestern United States and the Atlantic coast. *Bull. Amer. Meteor. Soc.*, **22**, 269-270.

——, 1950: Some aspects of the general circulation of the atmosphere. *Centennial Proceedings Royal Meteorological Society*, 120-155.

——, 1956: *Weather Analysis and Forecasting*, Vol. 1, 2nd ed. McGraw-Hill, 428 pp.

Reed, R., 1960: Principal frontal zones of the Northern Hemisphere in winter and summer. *Bull. Amer. Meteor. Soc.*, **41**, 591-598.

Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951-1970. *Mon. Wea. Rev.*, **102**, 861-868.

——, 1979: Trends in the frequencies of cyclone activity over North America. *Mon. Wea. Rev.*, **107**, 1684-1688.

Resio, D. and B. Hayden, 1975: Recent secular variations in mid-Atlantic winter extratropical storm climate. *J. Appl. Meteor.*, 14, 1223-1234.

Vincent, L., R. Dolan, B. Hayden and D. Resio, 1976: Systematic variations in barrier island topography. *J. Geol.*, **84**, 583-594.

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

Unclassified

3. REPORT TITLE

Secular Variation in Atlantic Coast Extratropical Cyclones

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Bruce Hayden

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
January 1981	9	25

8a. CONTRACT OR GRANT NO.

N00014-81-K-0033

b. PROJECT NO.

NR 389 170

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

Technical Report No. 23

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES

Reprinted from Monthly Weather Review, Vol. 109, no. 1, January 1981.

12. SPONSORING MILITARY ACTIVITY

Geography Programs
Office of Naval Research
Arlington, Virginia 22217

13. ABSTRACT

To define spatial and temporal variations in annual cyclone frequencies, principal components were calculated from a matrix of annual frequencies for 74 grid cells covering eastern North America and the western North Atlantic and the years 1885 to 1978. The first principal component contrasts cyclone frequencies in continental versus marine areas. Since the early years of this century, there has been a trend toward increased cyclone frequency over marine areas and a decline in frequencies over the continent. This trend peaked in the 1960s. The second principal component is interpreted as an east coast cyclogenesis function. Like the first component, it exhibits a century-long secular variation with increasing coastal cyclogenesis in recent decades and a maximum in the 1950s. The first two components explain 45% of the total variance. Higher order vectors (3rd and 4th) explained 12% of the variance and geographically depict variance in the Gulf coast and Great Lakes regions, respectively. Secular variations in the weightings of the third and fourth components contain higher frequency variations than the first and second components.

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cyclones Storms Extratropical Climate Climate change Atlantic Coast						

Unclassified
Security Classification

Technical Report No. 24

CYCLONE OCCURRENCE MAPPING:

EQUAL AREA OR RAW FREQUENCIES?

Bruce Hayden

Department of Environmental Sciences
University of Virginia
Charlottesville, Virginia 22903

January 1981

Geography Programs
Office of Naval Research
Contract No. N00014-81-K-0033

Reprint from Monthly Weather Review
Vol. 109, No. 1, January 1981

Reprinted from MONTHLY WEATHER REVIEW, Vol. 109, No. 1, January 1981
American Meteorological Society
Printed in U. S. A.

Cyclone Occurrence Mapping: Equal Area or Raw Frequencies?

BRUCE P. HAYDEN

Cyclone Occurrence Mapping: Equal Area or Raw Frequencies?

BRUCE P. HAYDEN

Department of Environmental Sciences, University of Virginia, Charlottesville 22903

29 February 1980 and 10 July 1980

ABSTRACT

Meteorological data extracted from maps and charts is frequently normalized for area because grid cell size changes with latitude. Raw and area-normalized cyclone frequency data were compared. Area normalization deforms mean frequency patterns. The patterns of standard deviations about the mean are not deformed in the same way. Area normalization does not change calculated principal components or their time histories of weightings.

1. Introduction

Ballenzweig (1959) detailed the advantages of equal-area grids in data extraction and in mapping the geographical distribution of physical quantities. He also listed the disadvantages of using latitude-longitude grid cells and of the subsequent use of latitude-dependent correction to achieve an area normalization. Ballenzweig's "practical" equal-area grid has not been widely used in data extraction from maps in spite of its merits. This has occurred, ironically, due to practical considerations arising from the diversity of scale and projection of historical data in map form. For detailed collection from maps, preparation of new equal-area grids each time scale projection changes is a major disadvantage. In almost all cases data are extracted from published maps according to grid cells defined by lines of latitude and longitude.

Judging from the recent literature (O'Connor, 1964; Taljaard, 1967; Reitan, 1974, 1979), latitude-dependent area normalization has become the method of choice even though Ballenzweig discourages its use in favor of raw frequencies in *n* degree squares. South of the reference latitude, area-normalization adjusts the frequency downward, to make it represent a box smaller than the one in which the original tabulations were made. The frequency of cyclones is thereby artificially decreased. North of the reference latitude a reverse problem exists, and cyclone frequencies are artificially increased. In a recent study on cyclone frequencies (Hayden, 1980) we examined the issue anew. We, like most investigators, did not construct equal-area grid cells for the data extraction process. This decision was one of convenience. The diversity on map formats for published tracks of cyclone centers between 1885 and 1979 weighed against constructing equal-area data collection grids. We have compared results of an analysis using area-normalized data with results using raw frequency totals, and found no significant differences between the two.

2. The test data

Cyclone frequencies for summers (April through September) for each year (1885–1979) were tabulated for the 74 2.5° latitude by 5.0° longitude grid cells comprising the study area shown in Fig. 1. From monthly charts of the "Tracks of the Centers of Cyclones at Sea Level" published by the *Monthly Weather Review* and in recent years by *Mariners Weather Log*, summer season totals of cyclones passing through each grid cell were recorded. Multiple entries into grid cells were ignored. Two test data matrices were prepared. One matrix consisted of the raw grid cell frequency data. The second matrix was area normalized for an area 10^5 km^2 using latitude-dependent, degree-to-length conversions published in Table 163 of the *Smithsonian Meteorological Tables*. In this study the reference latitude was north of all grid cells and thus frequencies are reduced at all locations. All grid cells in the study area are slightly larger than 10^5 km^2 with the largest departures in the lowest latitudes.

0027-0644/81/010168-05$05.25

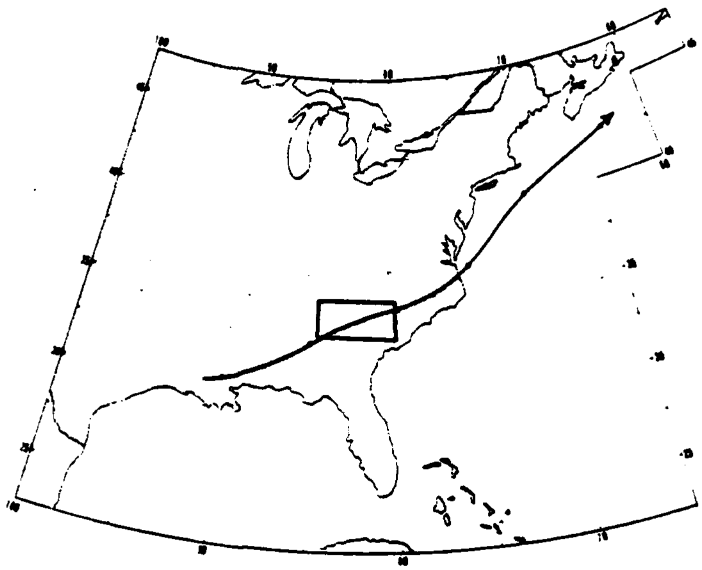


FIG. 1. Chart of the study area. The rectangular inset is 2.5° latitude by 5.0° longitude. There are 74 such rectangular grid cells in the study area. The arrow represents a storm track passing through the grid cell shown.

Long-term means and standard deviations of each matrix were calculated.

3. The means

Fig. 2 shows the means of summer cyclone frequencies for the raw frequency data, the area-normalized frequencies and the difference between the two mean charts. General inspection of the charts reveals little difference in the two means with the exception of slightly lower values in the area-normalized chart. The difference chart (Fig. 2c) shows that the deformation of the raw frequency caused by area normalization does not vary smoothly with latitude. The greatest difference is near latitude 40° where the raw frequency means are generally large.

4. The standard deviations

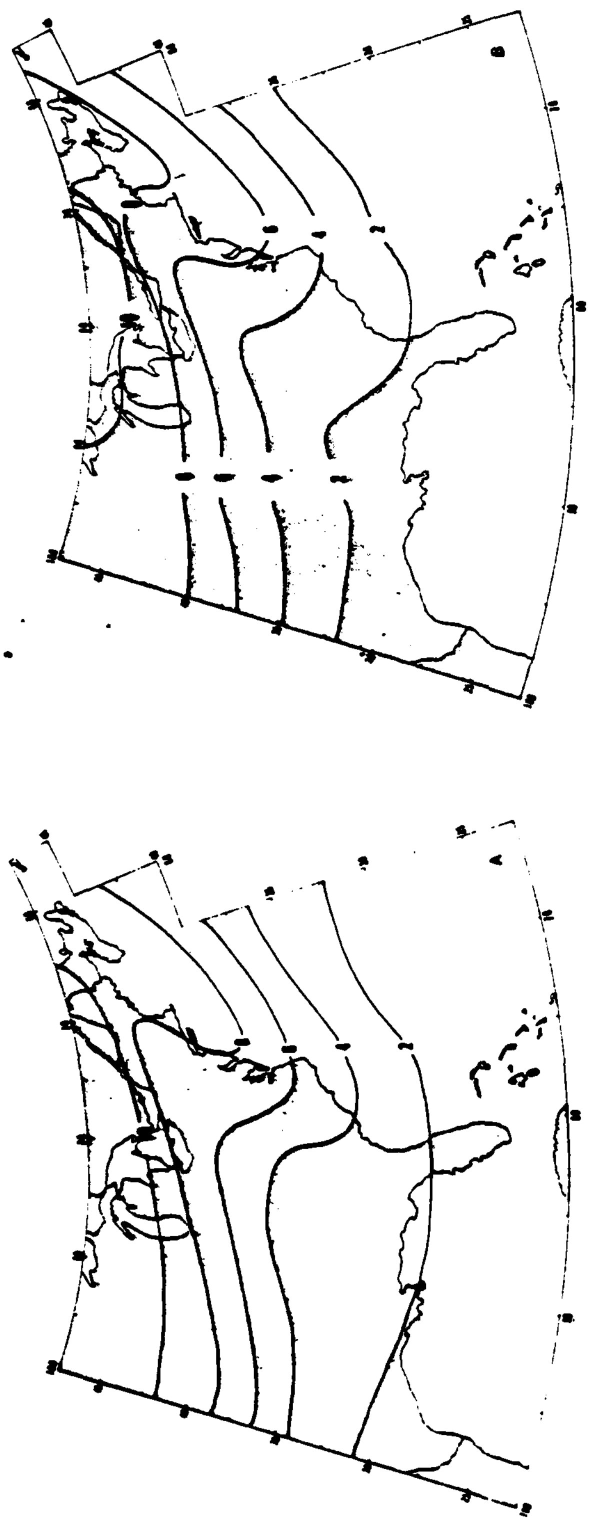
Fig. 3 shows the standard deviations associated with the mean summer cyclone frequencies shown in Fig. 2. The general pattern of the standard deviations of the raw and area-normalized frequency data are similar. As expected the standard deviations are slightly smaller everywhere. The difference between the two standard deviation charts again shows that the largest differences are near 40° latitude with the greatest reduction in the magnitude of the standard deviation occurring where the mean values tend to be highest. Again a simple latitudinal adjustment of the data results in a relatively complex deformation of the raw frequency data. The difference patterns for the two means and two standard deviations are not identical.

5. Discussion

The pattern deformation caused by an area normalization of the raw frequency data is in part dependent on the reference area of normalization. In this study 10^5 km^2 was selected because it was the best round number area closest to the actual size of the latitude-longitude grid cells used in the original data collection. This choice is common: Reitan (1974) used 5.5×10^5 km^2; Petterssen (1950) chose 10^5 km^2; Keegan (1958) used 10^5 mi^2. Klein (1958), Taljaard (1967), and O'Connor (1964) used a reference latitude-longitude grid cell at a specified latitude as their standard for area normalization.

Generally only the average frequency charts are presented and discussed. The deformation of mean patterns caused by area normalization would not seriously affect their interpretations. Equal-area adjustments do change frequency totals. This problem becomes serious if the area-normalized frequencies are plotted on unequal area map projections as is usually the case.

We have run tests and have found that area normalization results in no alteration of the principal components eigenvectors or the time histories of eigenvector weightings published earlier (Hayden, 1980). This is because the normalization of the data inherent in the formation of the correlation matrix, from which the eigenvectors were extracted, cancels



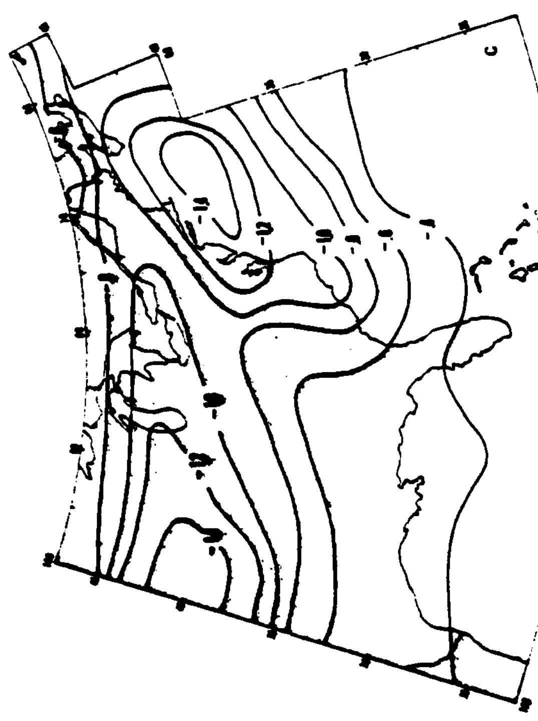


FIG. 2. Long-term (1885–1979) summer (April–September) mean cyclone frequencies: (a) raw frequencies, (b) area-normalized frequencies, and (c) difference between area normalized and raw frequencies.

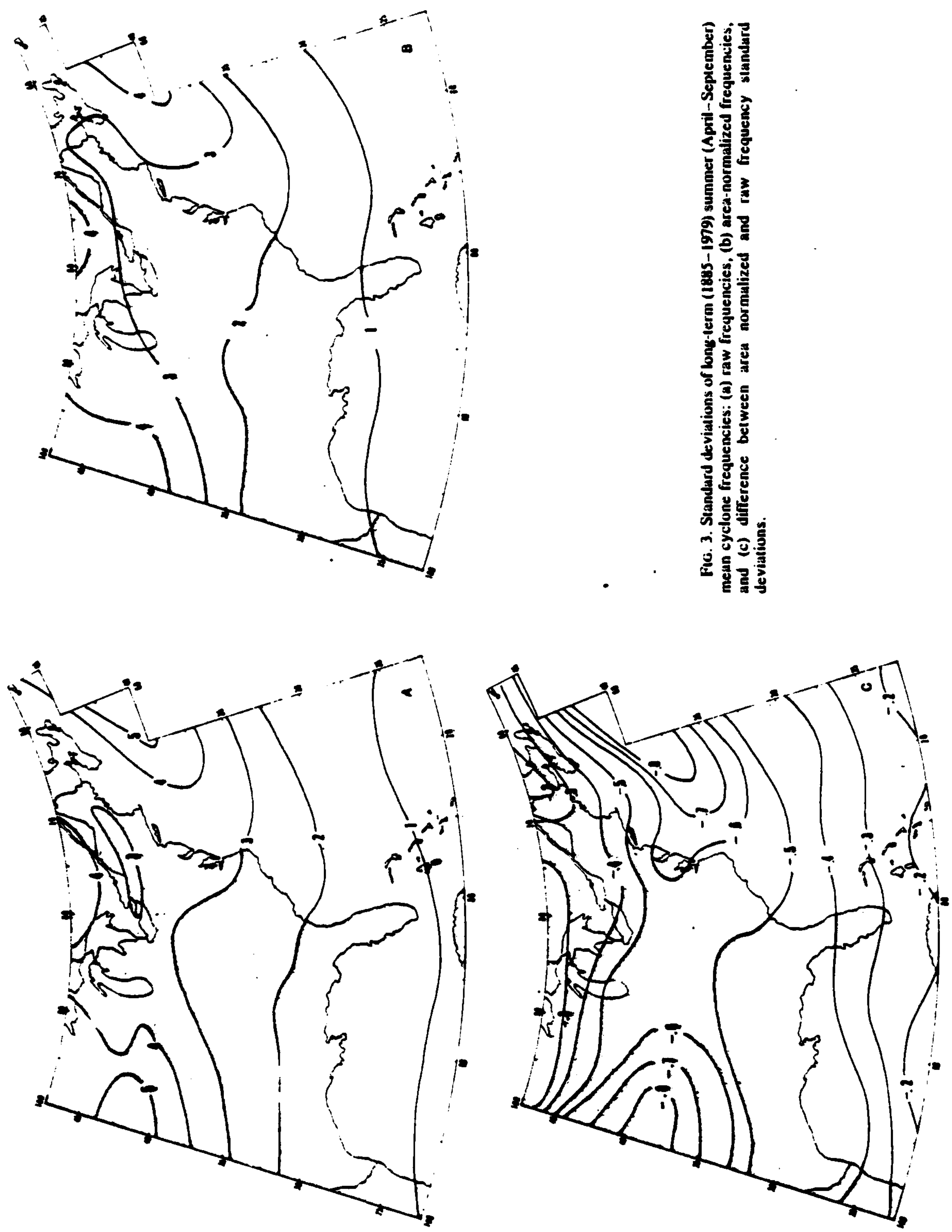


FIG. 3. Standard deviations of long-term (1885–1979) summer (April–September) mean cyclone frequencies: (a) raw frequencies, (b) area-normalized frequencies, and (c) difference between area normalized and raw frequency standard deviations.

the effects of any latitude-dependent scaling of the variables involved.

It is concluded that equal-area grids for data extraction are desirable, but unfortunately they are impractical. Latitude-dependent area adjustments, made after the data extraction is completed, introduce a latitude-dependent bias in the frequency patterns. Such latitude-dependent adjustments have been made by many investigators, but probably do not affect their results enough to alter their conclusions. However, it is recommended that area-normalization be avoided in future studies, because it introduces a systematic bias in the analysis.

REFERENCES

Ballenzweig, E. M., 1959: A practical equal-area grid. *J. Geophys. Res.*, **64**, 647–651.

Hayden, B., 1980: Atlantic coast extratropical cyclones—characteristic frequency patterns and their secular variation. *Preprints, Second Conf. Coastal Meteor.*, Los Angeles. Amer. Meteor. Soc., 192–197.

Keegan, T. J., 1958: Arctic synoptic activity in winter. *J. Meteor.*, **15**, 513–521.

Klein, W. H., 1958: The frequency of cyclones and anticyclones in relation to the mean circulation. *J. Meteor.*, **15**, 98–102.

O'Connor, J. F., 1964: Hemispheric distribution of 5-day mean 700-mb circulation centers. *Mon. Wea. Rev.*, **92**, 303–315.

Petterssen, S., 1950: Some aspects of the general circulation of the atmosphere. *Centennial Proceedings Royal Meteorology Society*, 120–155.

Reitan, C. H., 1974: Frequencies of cyclones and cyclogenesis for North America, 1951–1970. *Mon. Wea. Rev.*, **102**, 861–868.

——, 1979: Trends in the frequencies of cyclone activity over North America. *Mon. Wea. Rev.*, **107**, 1684–1688.

Taljaard, J. J., 1967: Development, distribution and movement of cyclones and anticyclones in the Southern Hemisphere during the IGY. *J. Appl. Meteor.*, **6**, 973–987.

Security Classification

DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Department of Environmental Sciences University of Virginia Charlottesville, VA 22903	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP Unclassified
3. REPORT TITLE Cyclone Occurrence Mapping: Equal Area or Raw Frequencies?	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates)	
5. AUTHOR(S) (First name, middle initial, last name) Bruce Hayden	
6. REPORT DATE January 1981	7a. TOTAL NO. OF PAGES 5 7b. NO. OF REFS 9
8a. CONTRACT OR GRANT NO. N00014-81-K-0033 b. PROJECT NO. c. NR 389 170 d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report No. 24 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
10. DISTRIBUTION STATEMENT Approved for public release; distribution unlimited	
11. SUPPLEMENTARY NOTES Reprinted from Monthly Weather Review, Vol. 109, no. 1, January 1981.	12. SPONSORING MILITARY ACTIVITY Geography Programs Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT

Meteorological data extracted from maps and charts is frequently normalized for area because grid cell size changes with latitude. Raw and area-normalized cyclone frequency data were compared. Area normalization deforms mean frequency patterns. The patterns of standard deviations about the mean are not deformed in the same way. Area normalization does not change calculated principal components or their time histories of weightings.

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Cyclones						
Climate mapping						
Storms						
Area normalization						

DD FORM 1 NOV 65 1473 (BACK)
(PAGE 2)

Unclassified
Security Classification

OCT. 26, 1977 JOB 460-101

SYSTEMATIC GEOGRAPHY LISTING

0001 1 OFFICE OF NAVAL RESEARCH 2 COPIES
0001 2 GEOGRAPHY PROGRAMS
0001 3 CODE 462
0001 4 ARLINGTON, VIRGINIA 22217

0002 1 DEFENSE DOCUMENTATION CENTER 12 COPIES
0002 2 CAMERON STATION
0002 3 ALEXANDRIA, VIRGINIA 22314

0003 1 DIRECTOR, NAVAL RESEARCH LAB 6 COPIES
0003 2 ATTENTION TECHNICAL INFORMATION OFFICER
0003 3 WASHINGTON, D. C. 20375

0004 1 DIRECTOR
0004 2 OFFICE OF NAVAL RESEARCH BRANCH OFFICE
0004 3 1030 EAST GREEN STREET
0004 4 PASADENA, CALIFORNIA 91101

0005 1 DIRECTOR
0005 2 OFFICE OF NAVAL RESEARCH BRANCH OFFICE
0005 3 536 SOUTH CLARK STREET
0005 4 CHICAGO, ILLINOIS 60605

0006 1 DIRECTOR
0006 2 OFFICE OF NAVAL RESEARCH BRANCH OFFICE
0006 3 495 SUMMER STREET
0006 4 BOSTON, MASSACHUSETTS 02210

0007 1 COMMANDING OFFICER
0007 2 OFFICE OF NAVAL RESEARCH BRANCH OFFICE
0007 3 BOX 39
0007 4 FPO NEW YORK 09510

0008 1 CHIEF OF NAVAL RESEARCH
0008 2 ASST. FOR MARINE CORPS MATTERS
0008 3 CODE 100M
0008 4 OFFICE OF NAVAL RESEARCH
0008 5 ARLINGTON, VIRGINIA 22217

0009 1 OFFICE OF NAVAL RESEARCH
0009 2 CODE 480
0009 3 NATIONAL SPACE TECHNOLOGY LABORATORIES
0009 4 BAY ST. LOUIS, MISSISSIPPI 39520

0010 1 OFFICE OF NAVAL RESEARCH
0010 2 OPERATIONAL APPLICATIONS DIVISION
0010 3 CODE 200
0010 4 ARLINGTON, VIRGINIA 22217

OCT. 26, 1977 JOB 460-101

SYSTEMATIC GEOGRAPHY LISTING

0011 1 OFFICE OF NAVAL RESEARCH
0011 2 SCIENTIFIC LIAISON OFFICER
0011 3 SCRIPPS INSTITUTION OF OCEANOGRAPHY
0011 4 LA JOLLA, CALIFORNIA 92093

0012 1 DIRECTOR, NAVAL RESEARCH LABORATORY
0012 2 ATTN LIBRARY, CODE 2628
0012 3 WASHINGTON, D. C. 20375

0013 1 ONR SCIENTIFIC LIAISON GROUP
0013 2 AMERICAN EMBASSY - ROOM A-407
0013 3 APO SAN FRANCISCO 96503

0101 1 COMMANDER
0101 2 NAVAL OCEANOGRAPHIC OFFICE
0101 3 ATTN. LIBRARY CODE 1600
0101 4 WASHINGTON, D. C. 20374

0102 1 NAVAL OCEANOGRAPHIC OFFICE
0102 2 CODE 3001
0102 3 WASHINGTON, D. C. 20374

0103 1 CHIEF OF NAVAL OPERATIONS
0103 2 OP 987P1
0103 3 DEPARTMENT OF THE NAVY
0103 4 WASHINGTON, D. C. 20350

0104 1 OCEANOGRAPHER OF THE NAVY
0104 2 HOFFMAN II BUILDING
0104 3 200 STOVALL STREET
0104 4 ALEXANDRIA, VIRGINIA 22322

0105 1 NAVAL ACADEMY LIBRARY
0105 2 U. S. NAVAL ACADEMY
0105 3 ANNAPOLIS, MARYLAND 21402

0106 1 COMMANDING OFFICER
0106 2 NAVAL COASTAL SYSTEMS LABORATORY
0106 3 PANAMA CITY, FLORIDA 32401

0107 1 LIBRARIAN
0107 2 NAVAL INTELLIGENCE
0107 3 SUPPORT CENTER
0107 4 4301 SUITLAND ROAD
0107 5 WASHINGTON, D. C. 20390

OCT. 26, 1977 JOB 460-101

SYSTEMATIC GEOGRAPHY LISTING

0112	1	OFFICER IN CHARGE
0112	2	ENVIRONMENTAL RESEARCH PRODCTN FCLTY
0112	3	NAVAL POSTGRADUATE SCHOOL
0112	4	MONTEREY, CALIFORNIA 93940
0201	1	COMMANDING GENERAL
0201	2	MARINE CORPS DEVELOPMENT AND
0201	3	EDUCATIONAL COMMAND
0201	4	QUANTICO, VIRGINIA 22134
0202	1	DR. A. L. SLAFKOSKY
0202	2	SCIENTIFIC ADVISOR
0202	3	COMMANDANT OF THE MARINE CORPS
0202	4	CODE MC-RD-1
0202	5	WASHINGTON, D. C. 20380
1001	1	DEFENSE INTELLIGENCE AGENCY
1001	2	CENTRAL REFERENCE DIVISION
1001	3	CODE RDS-3
1001	4	WASHINGTON, D. C. 20301
1002	1	DIRECTOR
1002	2	DEFENSE MAPPING TOPOGRAPHIC CENTER
1002	3	ATTN= CODE 50200
1002	4	WASHINGTON, D. C. 20315
1003	1	COMMANDING OFFICER
1003	2	U.S. ARMY ENGINEERING
1003	3	TOPOGRAPHIC LABORATORY
1003	4	ATTN= ETL-ST
1003	5	FORT BELVOIR, VIRGINIA 22060
1005	1	CHIEF, WAVE DYNAMICS DIVISION
1005	2	USAE-WES
1005	3	P. O. BOX 631
1005	4	VICKSBURG, MISSISSIPPI 39180
2003	1	NATIONAL OCEANOGRAPHIC DATA
2003	2	CENTER (D764
2003	3	ENVIRONMENTAL DATA SERVICES
2003	4	NOAA
2003	5	WASHINGTON, D. C. 20235
2005	1	CENTRAL INTELLIGENCE AGENCY
2005	2	ATTENTION OCR/DD-PUBLICATIONS
2005	3	WASHINGTON, D. C. 20505

OCT. 26, 1977 JOB 460-101

SYSTEMATIC GEOGRAPHY LISTING

2007	1	DR. MARK M. MACOMBER
2007	2	ADVANCED TECHNOLOGY DIVISION
2007	3	DEFENSE MAPPING AGENCY
2007	4	NAVAL OBSERVATORY
2007	5	WASHINGTON, D. C. 20390
5001	1	MINISTERIALDIREKTOR DR. F. WEVER
5001	2	RUE/FO
5001	3	BUNDESMINISTERIUM DER VERTEIDIGUNG
5001	4	HARDTHOEHE
5001	5	D-5300 BONN, WEST GERMANY
5002	1	OBERREGIERUNGSRAT DR. ULLRICH
5002	2	RUE/FO
5002	3	BUNDESMINISTERIUM DER VERTEIDIGUNG
5002	4	HARDTHOEHE
5002	5	D-5300 BONN, WEST GERMANY
5003	1	MR. TAGE STRARUP
5003	2	DEFENCE RESEARCH ESTABLISHMENT
5003	3	OSTERBROGADES KASERNE
5003	4	DK-2100 KOBENHAVN O, DENMARK
5302	1	IR. M. W. VAN BATENBERG
5302	2	PHYSISCH LABORATORIUM TNO
5302	3	OUDE WAALSDORPER WEG 63, DEN HAAG
5302	4	NETHERLANDS
8002	1	COASTAL STUDIES INSTITUTE
8002	2	LOUISIANA STATE UNIVERSITY
8002	3	BATON ROUGE, LOUISIANA 70803
8003	1	DR. CHOULE J. SONU
8003	2	TETRA TECH, INC.
8003	3	630 NORTH ROSEMEAD BOULEVARD
8003	4	PASADENA, CALIFORNIA 91107
9001	1	DR. LESTER A. GERHARDT
9001	2	RENNSSELAER POLYTECHNIC INSTITUTE
9001	3	TROY, NEW YORK 12181
9002	1	MR. FRED THOMSON
9002	2	ENVIRONMENTAL RESEARCH INSTITUTE
9002	3	P.O. BOX 618
9002	4	ANN ARBOR, MICHIGAN 48107

OCT. 26, 1977   JOB 460-101

SYSTEMATIC GEOGRAPHY LISTING

9004	1	DR. THOMAS K. PEUCKER
9004	2	SIMON FRASER UNIVERSITY
9004	3	DEPARTMENT OF GEOGRAPHY
9004	4	BURNABY 2, B. C., CANADA
9005	1	DR. ROBERT DOLAN
9005	2	DEPARTMENT OF ENVIRONMENTAL SCIENCES
9005	3	UNIVERSITY OF VIRGINIA
9005	4	CHARLOTTESVILLE, VIRGINIA 22903

DA
FILM